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HUBBLE SPACE TELESCOPE PROJECT



Hubble Space Telescope Battery Capacity Trend Studies

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2003 NASA Aerospace Battery Workshop



Battery cell wear out mechanisms and signatures are examined and compared to orbital data from the six on-orbit Hubble Space Telescope (HST) batteries, and the Flight Spare Battery (FSB) Test Bed at Marshall Space Flight Center (MSFC), which is instrumented with individual cell voltage monitoring. Capacity trend data is presented which suggests HST battery replacement is required in 2005-2007 or sooner.



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HST Nickel Hydrogen (NiH_2) Cell Design Description



- Eagle Picher Technologies (EPT) RNH 90-3
- Air Force MANTECH Design
- Rabbit Ear Terminals
 - Graduated Leads
- Double Layer Zircar Separator
- Back-to-Back Electrode Configuration, 48 Plates
 - Zirconia Wall Wick
- Dry Sinter Nickel Plaque (84% Porosity)
 - EPT-Colorado Springs Plaque
 - Aqueous Chemical Impregnation
 - EPT-Joplin Impregnation & Assembly
- 27% KOH (At Discharged)
- Slight H_2 Pre-Charge

The on-orbit HST batteries were manufactured on an expedited basis after the Challenger Shuttle Disaster in 1986. The original design called for the HST to be powered by six 50 Ah Nickel Cadmium batteries, which would have required a shuttle mission every 5 years for battery replacement. The decision to use NiH_2 instead has resulted in a longer life battery set which was launched with HST in April 1990, with a design life of 7 years that has now exceeded 13+ years of orbital cycling. This chart details the specifics of the original HST NiH_2 cell design.

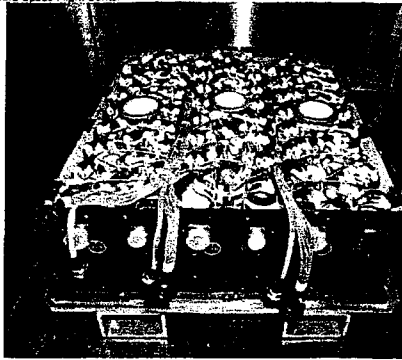
The HST replacement batteries for Service Mission 4 in Spring 2005 are currently in cold storage at Goddard Space Flight Center (GSFC). These utilize slurry process electrodes having 80% porosity.



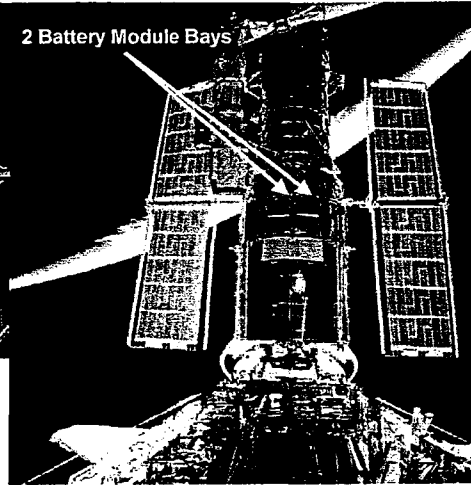
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HST Flight Batteries



2 Battery Module Bays



- (3) 23-cell NiH₂ Batteries Per Module
 - 22 Cells Electrically in Series
- Battery Module Size (in.):
 - 11.22 X 36.00 X 31.75
- Module Weight(lb.): 500 Max
- Battery Capacity: 88 Amp-hr (Ah)
 - 15 A Discharge to 26.4 V at 10 °C
- Launch: April 24, 1990 (13+ Years)
- Part No:4177755

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A total of 16 batteries were manufactured for the HST Program - 3 Flight Modules, 2 Test Modules, and a Flight Spare Battery. The 23-cell batteries only used 22 cells connected electrically in series. The 23rd cell was determined as driving the system voltage outside the voltage limits of some electronic boxes. The six on-orbit batteries are enclosed in 2 modules, like the one shown on the left here, each module has 3 batteries. Flight Module 2 (FM2) is mounted inside Equipment Bay Door #3, and the Flight Spare Module (FSM) is mounted inside Equipment Bay Door #2. Flight Module 1 (FM1) was re-designated as the "spare".



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HST Resources



- On-Orbit HST Batteries
 - Flight Module 2 (FM2) & Flight Spare Module (FSM)
 - Six 23-Cell Batteries - Launched 4/1990
 - 73.5K Cycles - (13+ Years)
- Marshall Space Flight Center (MSFC) HST Flight Spare Battery (FSB)
 - 23-Cell Battery - Cycled Started 6/1989
 - 78 K Cycles - (14+ Years)
 - Individual Cell Voltage Monitor
- MSFC Six Battery System Test - Test Module 1 (TM1) & TM2
 - Six 23-Cell Batteries - Cycled Started 5/1989
 - 78K Cycles - (14+ Years)
 - Individual Cell Voltage Monitor
- Flight Module #1 (FM1) Re-designated as "Flight Spare"
 - Three 23-Cell Batteries
 - Cold Stored @ EPT
 - Currently at Goddard Space Flight Center (GSFC)
 - Used for Test Equipment Checkout & Fit Checks



The 16 NiH₂ batteries manufactured for HST, most of which are the resources used in this analysis. Six batteries have been deployed since 1990 on HST and 7 batteries are being tested since 1989 at MSFC on two test beds. The test beds are utilized to evaluate system and battery control issues. These assets have slightly more cycles than the orbital batteries. The remaining 3 batteries are in FM1 which is designated the flight spare.

The Flight Spare Battery (FSB) and the Six Battery System Test Modules (TM1 & TM2) used for ground studies at MSFC are unique, in that they have individual cell monitoring, which provides very useful insight into individual cell ageing processes.



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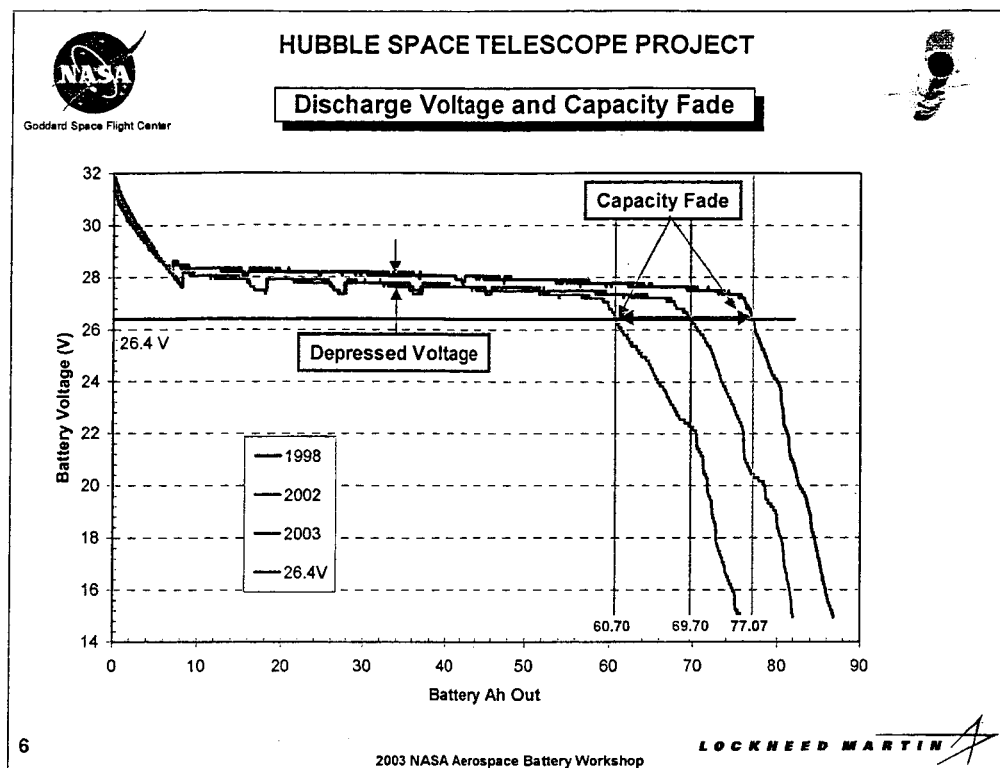
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Cell Battery Ageing Signatures

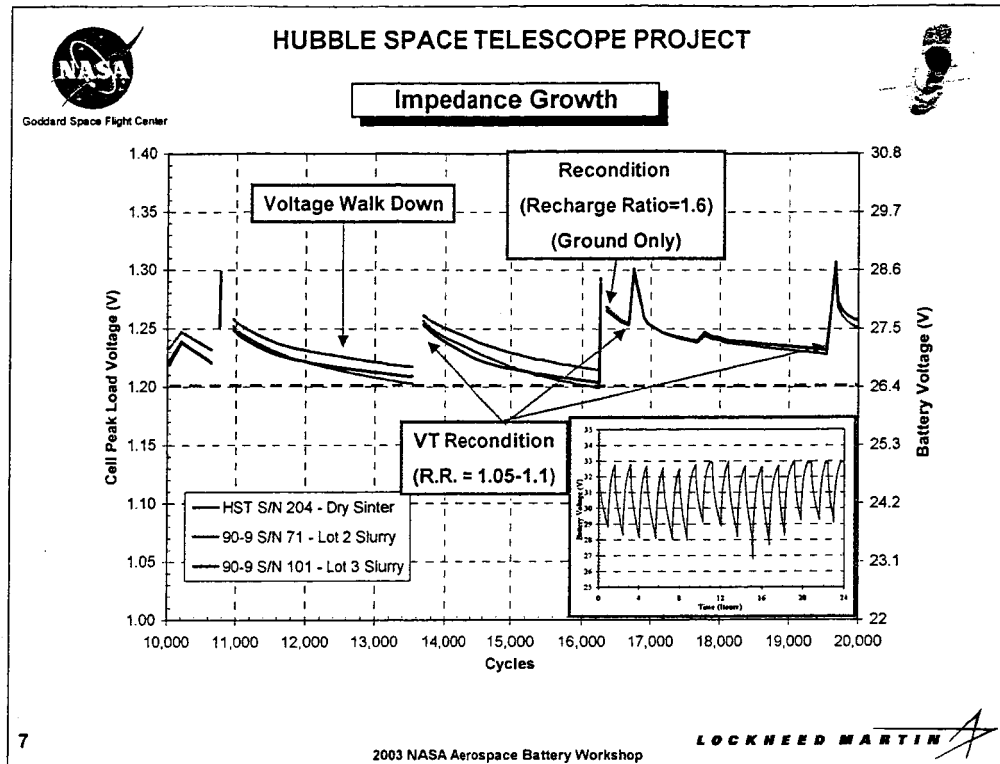


- Voltage Plateau Degradation And Capacity Fade
- Impedance Growth
- Cell Drop Out
- Second Plateau Formation And Cell Reversal

During this paper we will show several cell ageing signatures which occur in NiH_2 batteries with Low Earth Orbital (LEO) cycling.

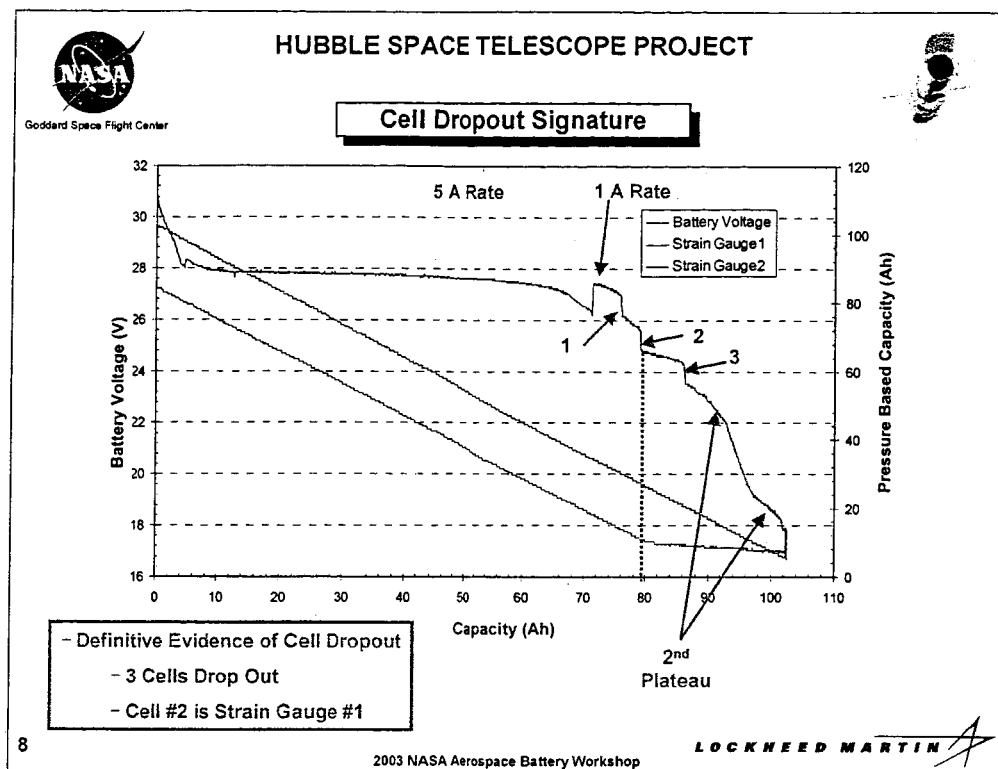


In addition to voltage walk down, several additional observed signatures are shown here, namely depressed voltage plateau and capacity fade. The various bumps and inflections in the voltage curves below 26.4 V are also indicative of cell degradation processes.



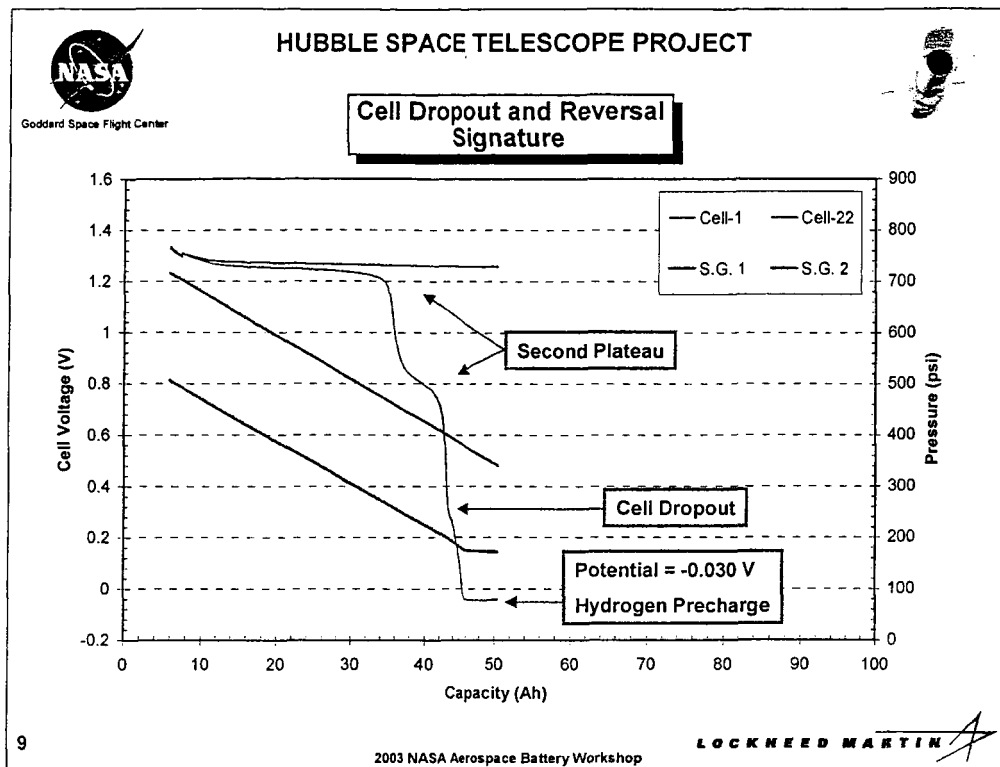
Demonstrated on this slide is the impedance growth which is observed by decay of the peak load voltage (see insert), or minimum voltage, during LEO cycling, of ground test cells, at 10-20 % Depth-of-Discharge (DOD). To restore system bus voltage, batteries must be reconditioned and charged to a temperature compensated Voltage-Temperature (VT) Levels that are designed within thermal limitations and with recharge ratios (RR) of 1.05 - 1.10. Ground reconditioning to a RR of 1.6 has been shown to restore the cell's usable capacity near beginning of life (BOL) levels. This has been observed during LM-Comsat electrical testing of aged cells.

For satellites which use a Battery Dominated Bus such as HST, the required minimum voltage at the battery terminals is 26.4 V.



This chart is from a Comsat design 22-cell battery (Hydrogen pre-charge and asbestos separator) with two strain gauges. The gauges monitor cell pressure and are a linear function of cell capacity. Note that Strain Gauge #1 is indicating 20 Ah less capacity at the beginning of this 5 A reconditioning discharge. Also note that this strain gauge pegs low at the exact same point as a major >800 mV sudden drop in the battery voltage (indicated by #2). This observation suggests that with sudden changes in battery voltage of >800 mV during reconditioning, there are probably 3 cells out of 22, that are dropping out and go to reversal as noted. The minor inflections, after the third cell drops out, are probably associated with the characteristic second plateau.

Theoretically the raw voltage from the HST strain gauge Wheatstone bridge circuit is linear from 0 psi to 1500 psi. This low-level voltage is then amplified, for telemetry, which due to amplifier low voltage threshold, pegs at about 150 psi. The SM4 HST cells have a newer amplifier circuit which has full amplified resolution from 0 to 1400 psi.



This chart, detailing the strain gauge cell voltage and strain gauge pressures from the capacity check for TM1 Battery 1, performed in 2002, reveals the relationship between cell drop out and hydrogen depletion, as evidenced by the Cell #22 and the strain gauge reading for S.G. #2.

Note that the cell voltage for cell #22 drops out and reverses reverses at the same time as its strain gauge pressure pegs, and the wide disparity between the two strain gauge pressures, and their respective cell voltages. This indicates the two cells have a capacity difference of at least 20+ Ah as evidenced by a 200+ psi pressure difference.

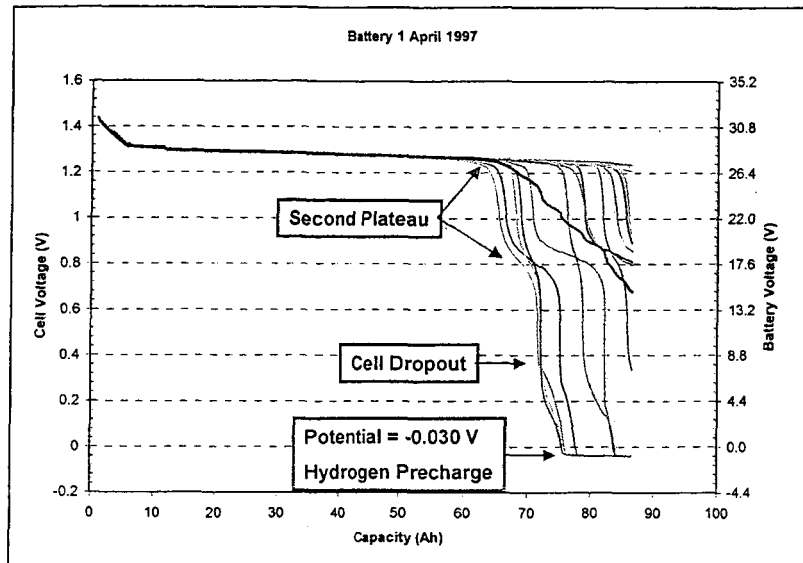
The cell reversal to a voltage of -30 mV is a voltage signature of hydrogen precharge cells. Nickel precharge cells would have a voltage signature of -400 mV upon cell reversal. (Al Zimmerman Report)



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2nd Plateau and Cell Reversal Signatures



Shown here, by the heavy blue line, is the battery discharge curve during a reconditioning cycle of TM1 Battery1 (1997). Comparing the battery trace with traces from the individual cells in this battery, additional signatures are shown for second plateau formation, and cell reversal (cell drop out).



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Flight Spare Battery

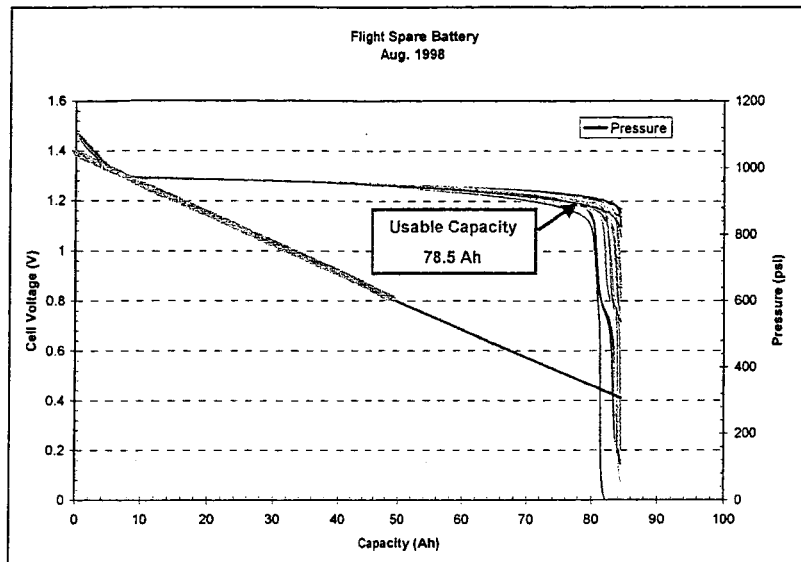
Ageing Signatures



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FSB - August, 1998 - 9 Years



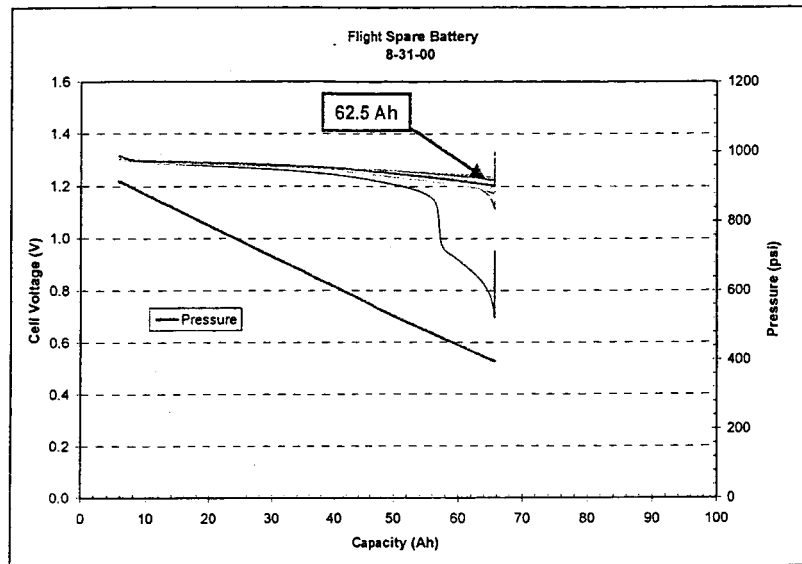
This chart details the individual cell voltages and pressure during a capacity discharge test conducted upon the FSB at MSFC after 9 years cycling. This test shows very little second plateau formation and little capacity dispersion between cells.



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FSB - August 2000 - 11 Years

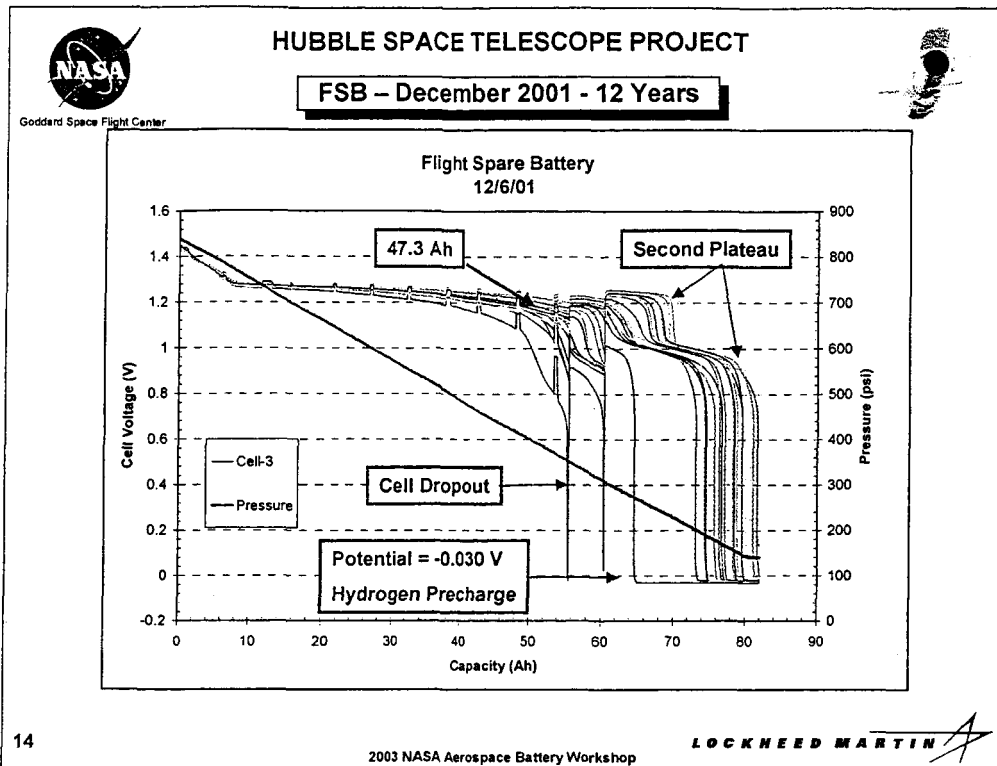


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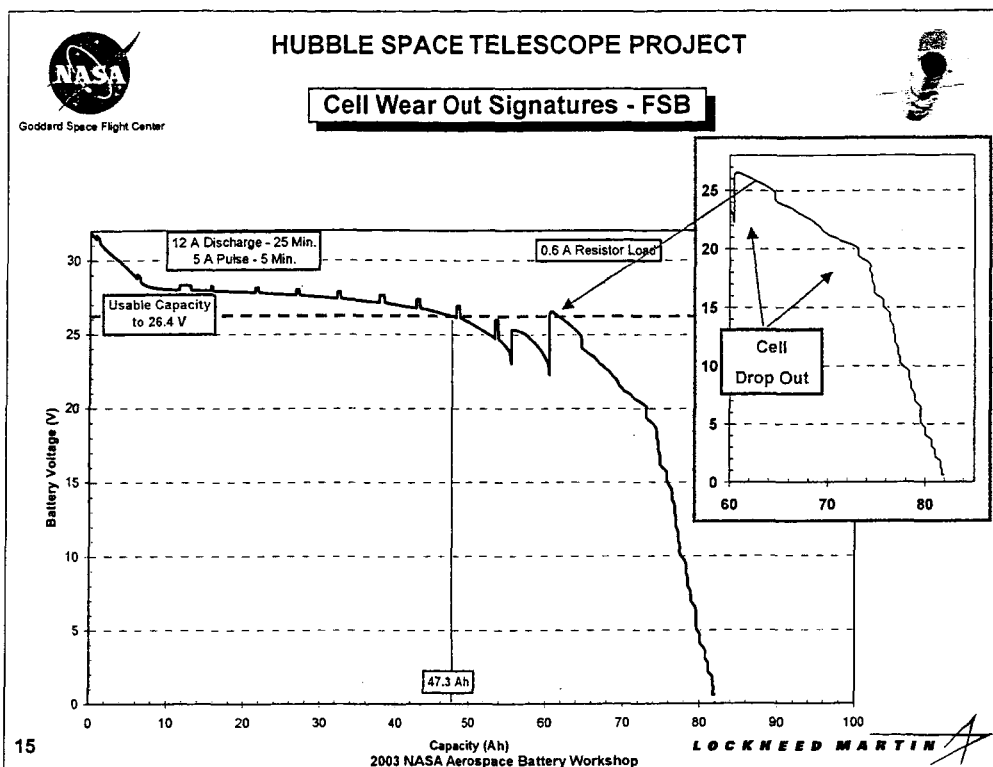
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This chart details a capacity discharge test conducted upon the FSB cycled for 11 years; note a cell diverging, a distinct 2nd plateau, and capacity fade which are not apparent for the capacity test at 9 years. The strain gauge (Cell #1) indicates that when the FSB reaches 26.4 V there is still ~400 psi (~40 Ah capacity) left in that cell.

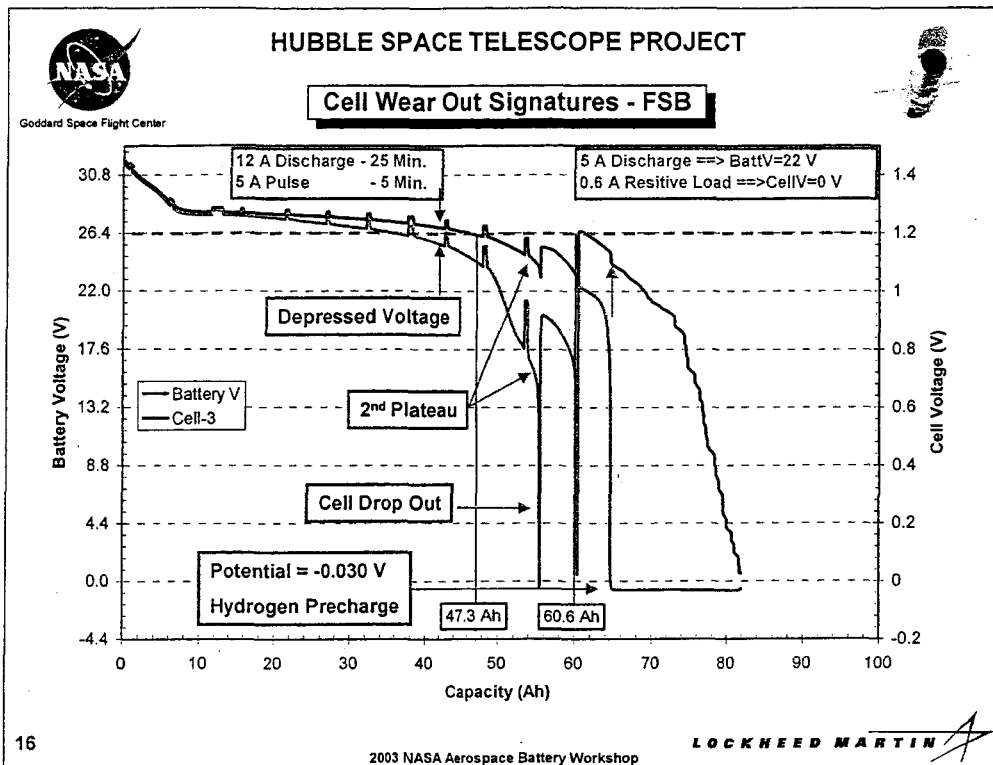


This chart details a capacity discharge test conducted upon the FSB after 12 years cycling (in 2001); note one cell dropping out before the remaining cells. The significant second plateau shows 30-40 Ah capacity still available to cell voltage of 0.8 V, but unusable. The strain gauge pressure is also shown here.

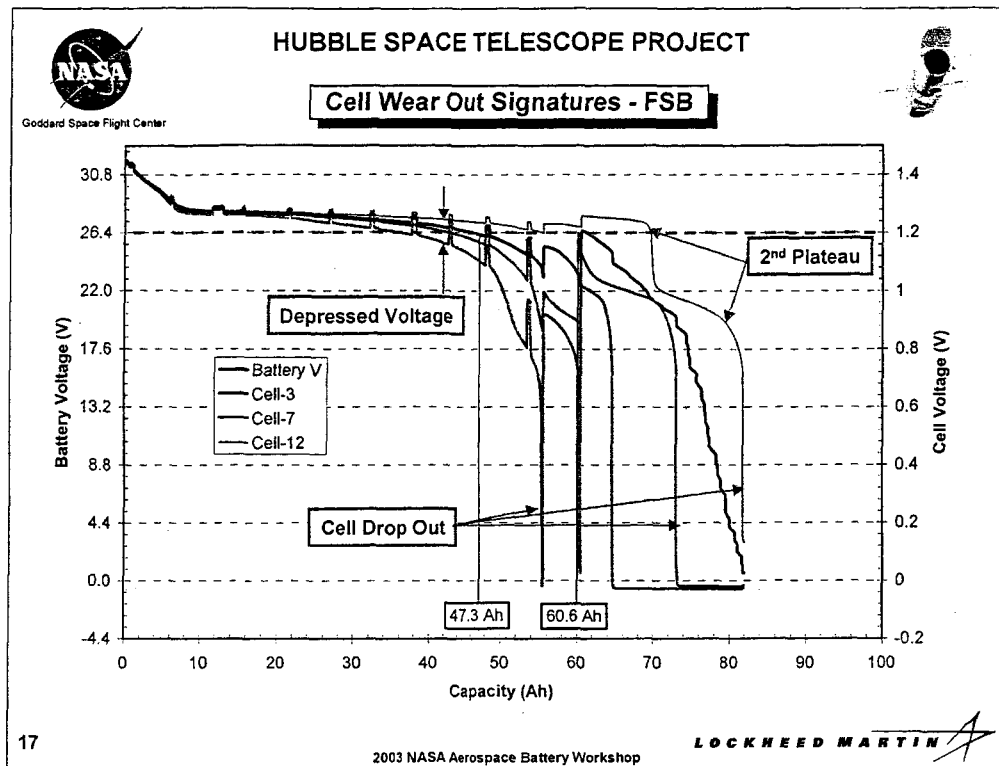


This is the battery voltage for the capacity discharge test shown on the previous slide. The normal 12 A discharge was modified to include 5 A pulses at 15 minute intervals. Dual discharge curves thus obtained have been used for cell modeling of impedance as a function of State-of-Charge (SOC).

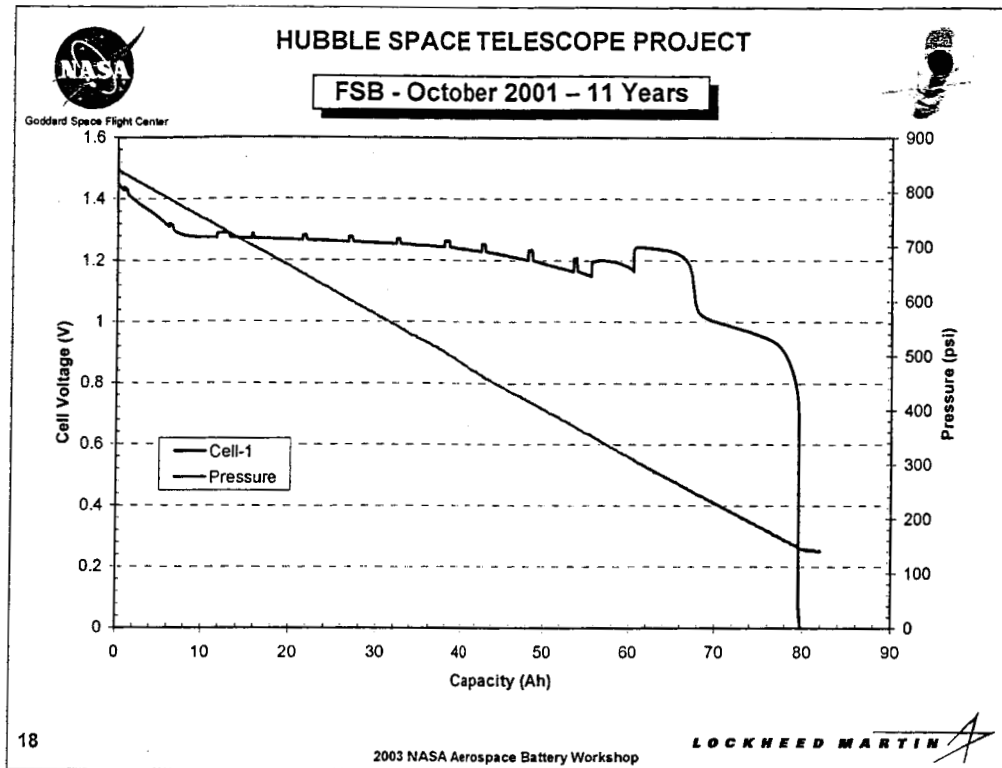
Note that this battery exhibits a usable capacity (to 26.4 V) of 47.3 Ah. Additionally there are several sharp deflections in the discharge curve beyond 64 Ah with delta-voltage (dV) in excess of 0.8 V as shown in the insert. These deflections will be shown as being due to cell drop outs in the following several slides.



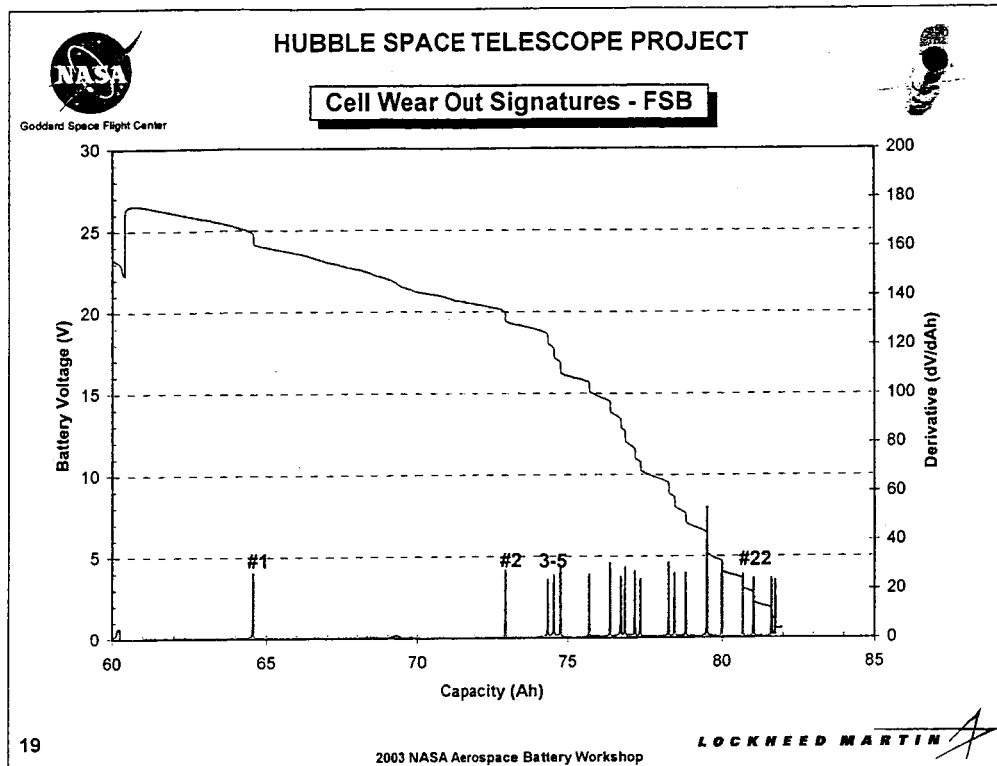
This slide shows the discharge voltage curves for the battery and cell #3; note depressed voltage and cell drop out which occurs at about 64 Ah with a dV in excess of 0.8 V. This corresponds to a similar drop in the battery voltage trace. The next slide gives additional confirmation.



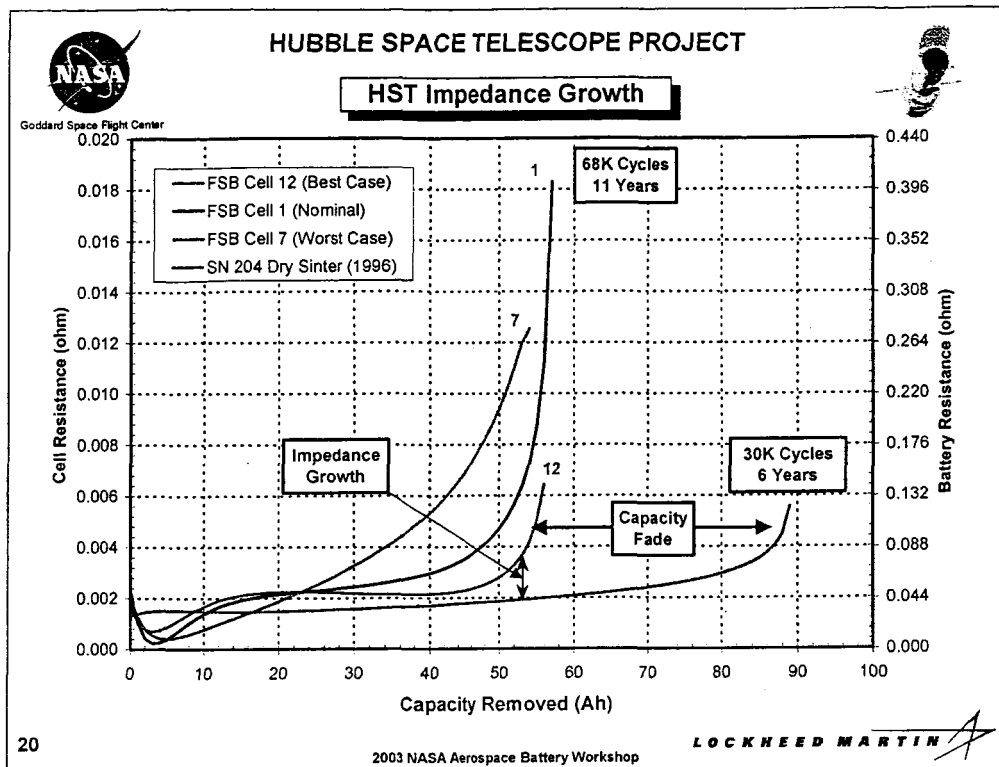
This slide shows the discharge voltage curves for the battery and representative cells #3, 7 and 12; note depressed voltage and additional cell drop out for cell #7 which occurs at about 73 Ah with a dV in excess of 0.8 V. The discharge voltage plateau degradation between cell #12 versus #3 and #7 is also substantial. The second plateau equates to the smaller inflections in the battery voltage curve.



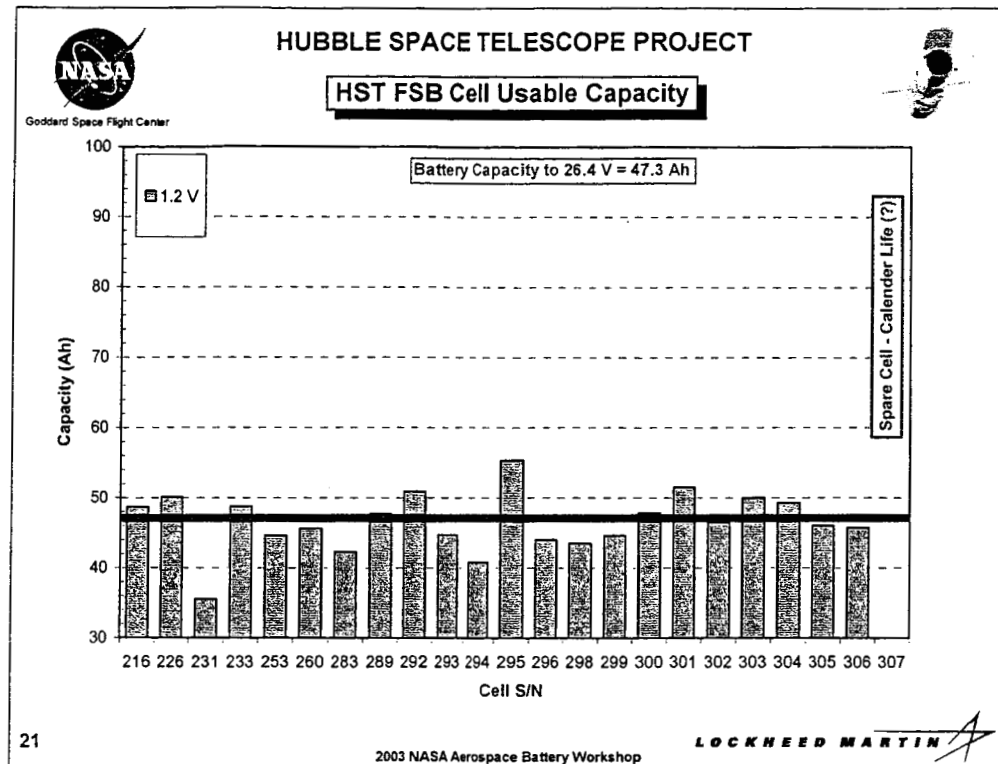
This slide shows that cell #1, having the only strain gauge on the FSB, goes into reversal (cell drop out) at the same time that its strain gauge reaches minimum pressure.



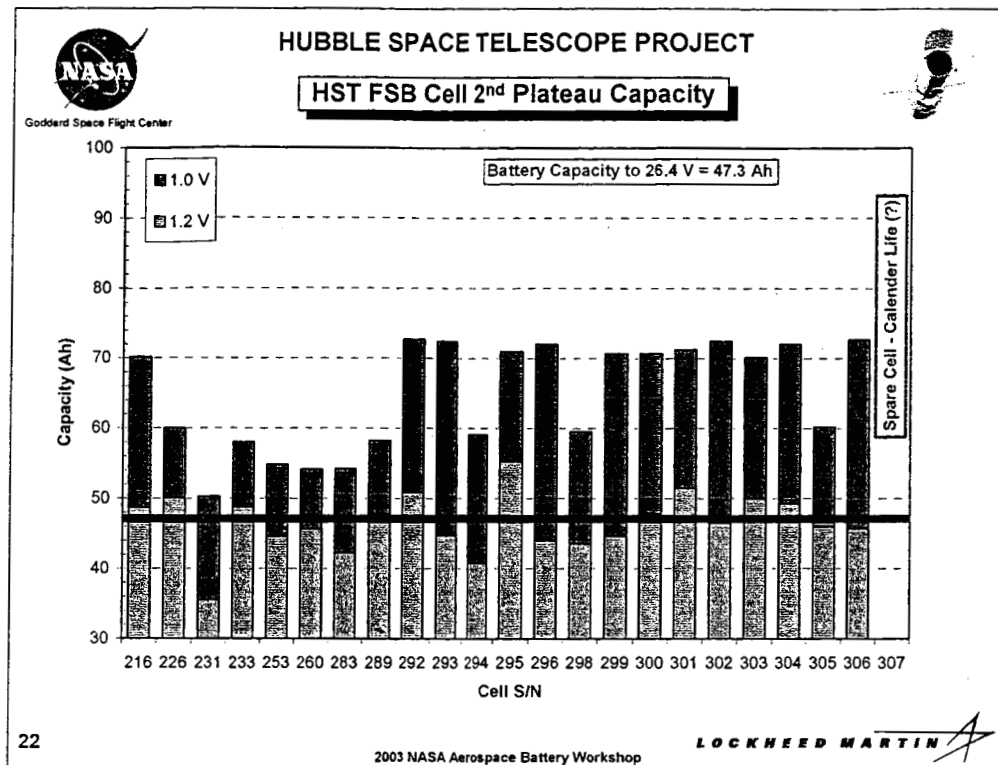
This chart examines the battery voltage versus capacity, between 60 and 85 Ah for the FSB, and compares the battery voltage drops with the derivative of voltage versus Ah capacity (dV per dAh). Note that each drop in the battery voltage equates with a spike in the derivative.



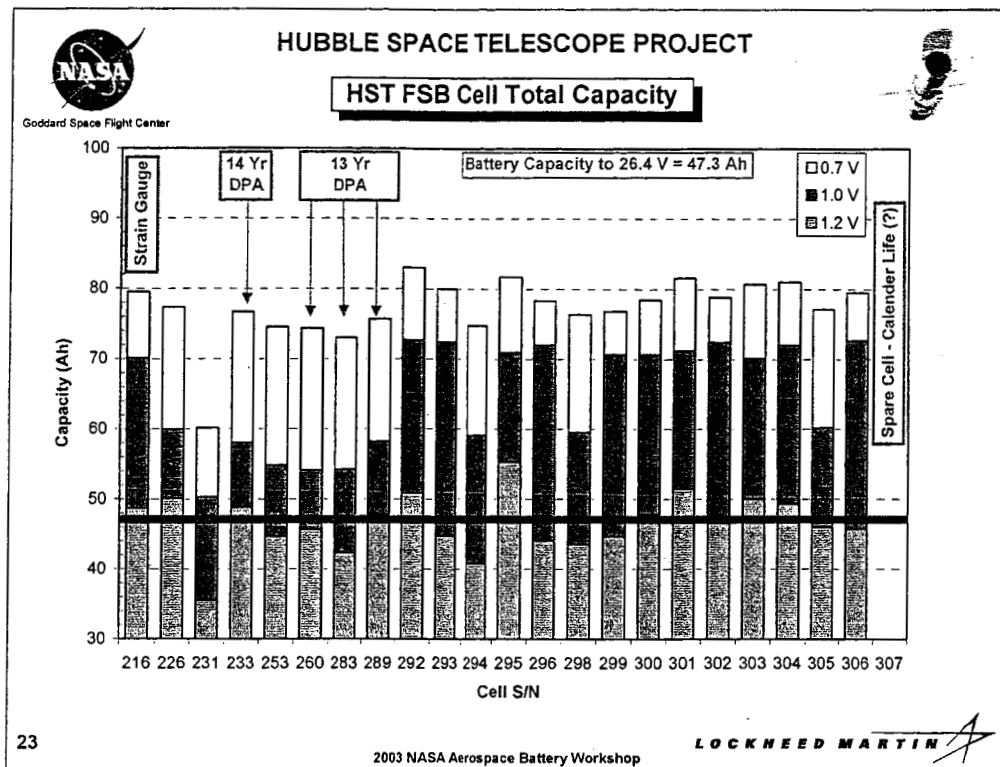
This chart examines the extracted impedance data obtained from the special pulse discharge test and compares it to a cell having minimal cycling; note the decrease in available capacity, the increase in cell impedance, and the wide dispersion in impedance for the 11 years old Flight Spare Battery cells. Only three representative cells of the 22 are shown here.



This chart details the spread of the individual cell usable capacities; note the spread of capacity ranges from 35 Ah for cell #3 (S/N 231) to a high of 55 Ah for cell #12 (S/N 295). The usable capacity for the battery to 26.4 V is 47.3 Ah. Cell #23 (S/N 307 - the electrically inactive cell) represents a cell having calendar life degradation only, with the same thermal exposures.



This chart details the spread of the individual cell capacities to cell voltages of 1.0 V and to 1.2 V; note the spread of capacity fade to 1.0 V tracks that of 1.2 V with very similar second plateau capacities between cells.



This chart details the spread of the individual cell total capacities to 0.7 V, with 1.2 V usable capacity and 1.0 V 2nd plateau capacity; note the total capacity ranges from 74 to 84 Ah for all cells except cell #3 (S/N 231) which only exhibits a total capacity of 60 Ah suggesting a severe cell wear out. The cells removed for Destructive Post-Analysis (DPA) by LM-Comsat are indicated. We are recommending that cells S/N 294 (low Ah), 231 (reversed & possible leaker(?)), 295 (high Ah), and cell #23 (calendar life with no electrical cycling) be subjected to DPA at a future date.



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HST Six Battery System Test Bed

Ageing Signatures

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Like the FSB, the 6-Battery System Test Bed (the six batteries of the TM1 and TM2 modules) have individual cell monitoring which provides very useful insight into individual cell ageing signatures.



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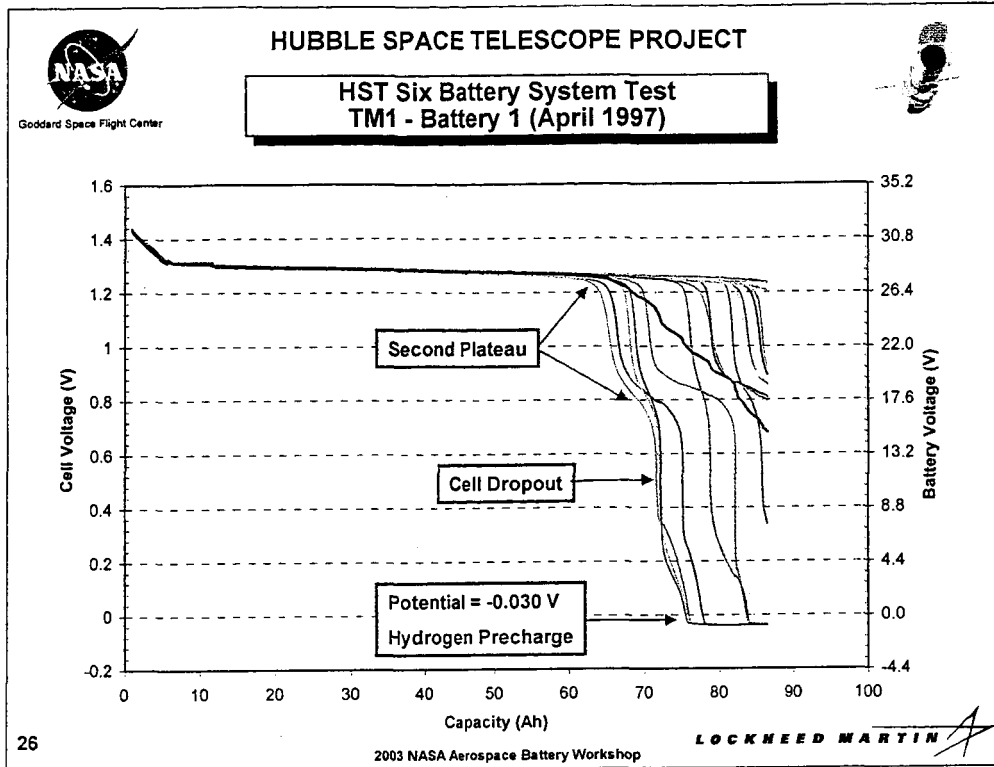
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HST Six Battery System Test Bed Cell/Battery Ageing Signatures

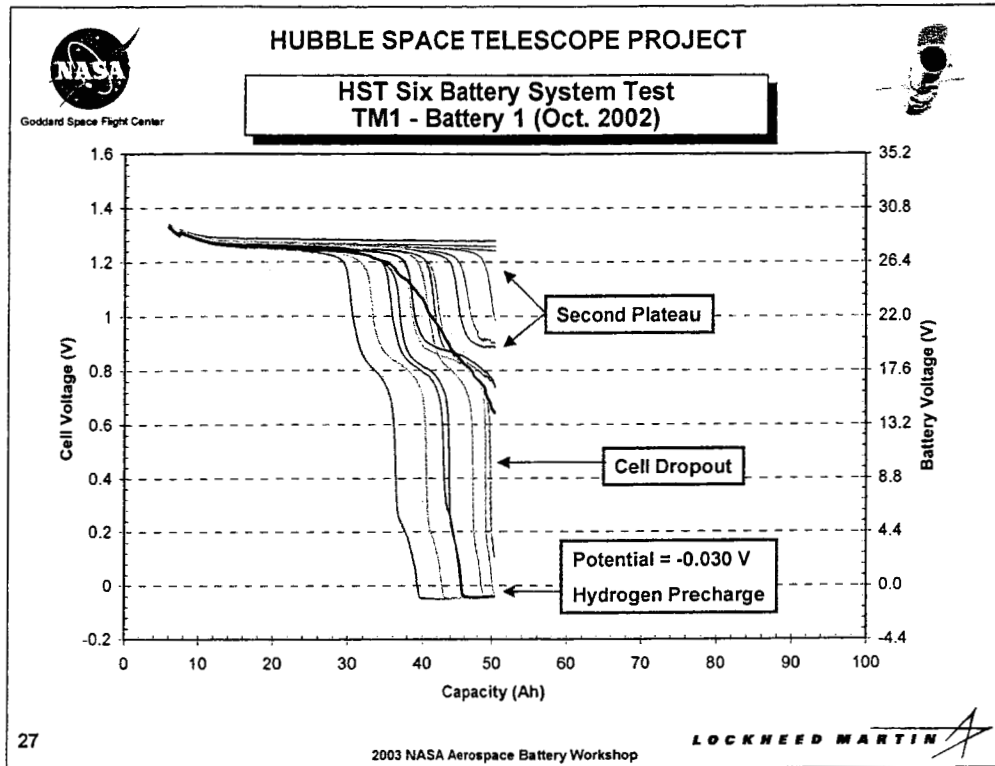


- Discharge Voltage Plateau Depressed on All Batteries
- Capacity Fade Observed on All Batteries
- Cell Drop-Out Observed On All Batteries
 - Signature is sudden >0.8 V Drop in Battery Voltage
 - Corresponds to Strain Gauge Minimum
- Second Plateau Observed on All Batteries
 - Signature <0.5 V

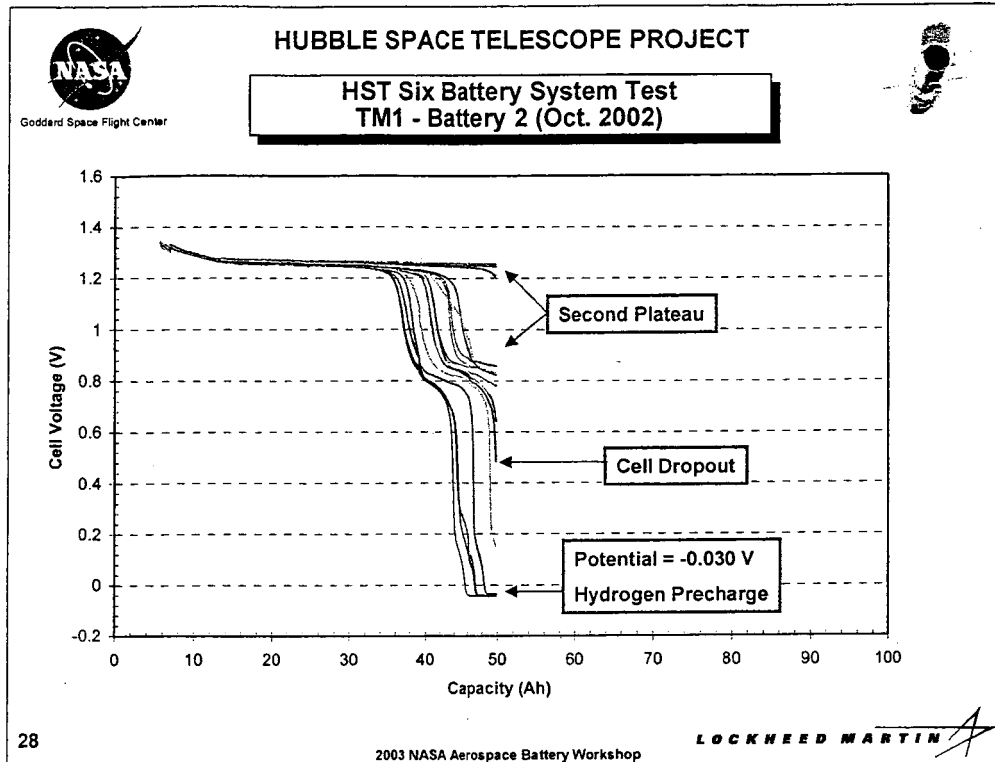
Like the FSB, the 6-Battery System Test Bed exhibits several cell ageing signatures with LEO cycling.



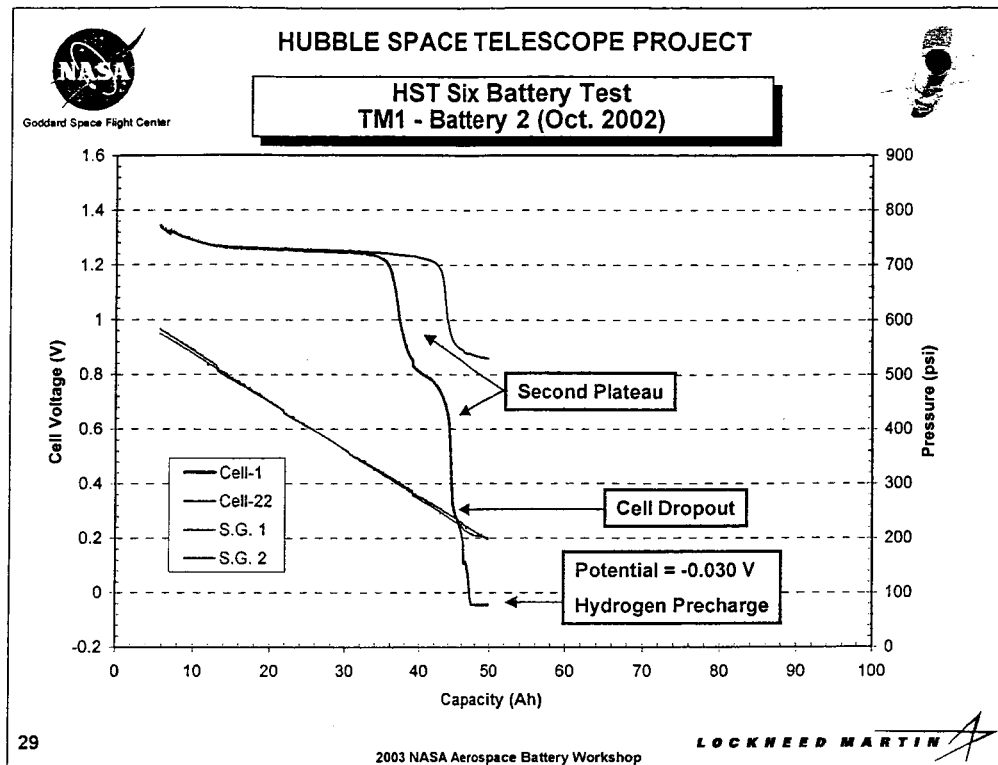
The 6-Battery TM1 and TM2 capacity check was performed in 1997. TM1 Battery 1 exhibits cell drop outs, 2nd plateaus, and a wide dispersion of cell capacities.



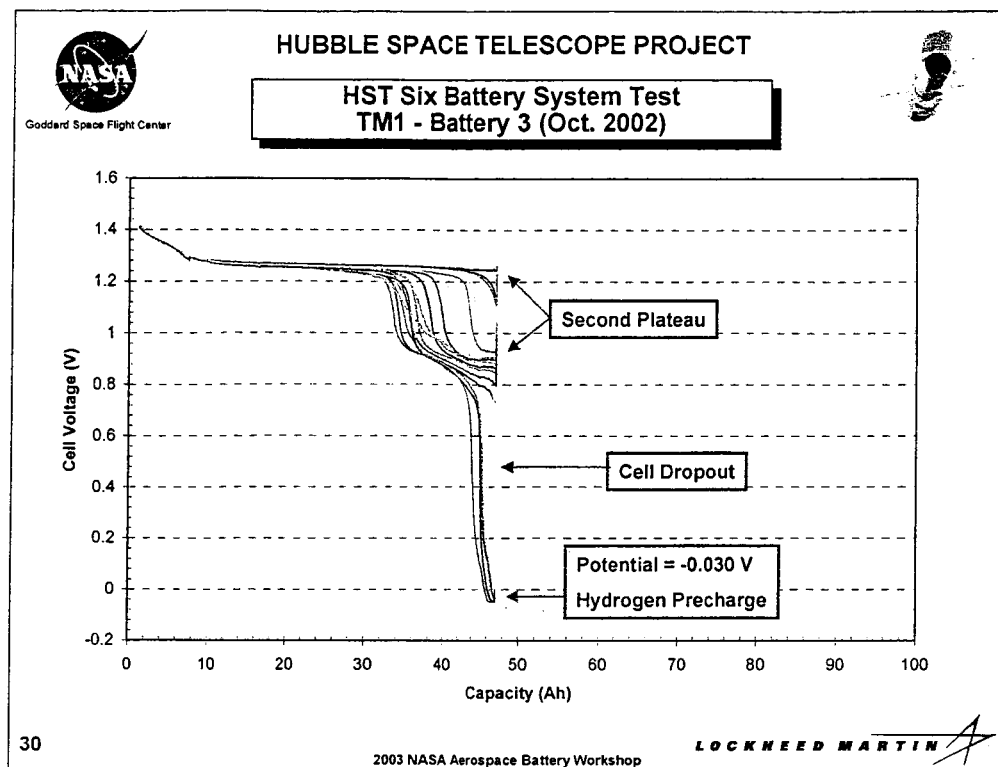
Five years later (2002), the capacity check for TM1 Battery 1 exhibits significant capacity fade, 2nd plateau, and cell drop outs.



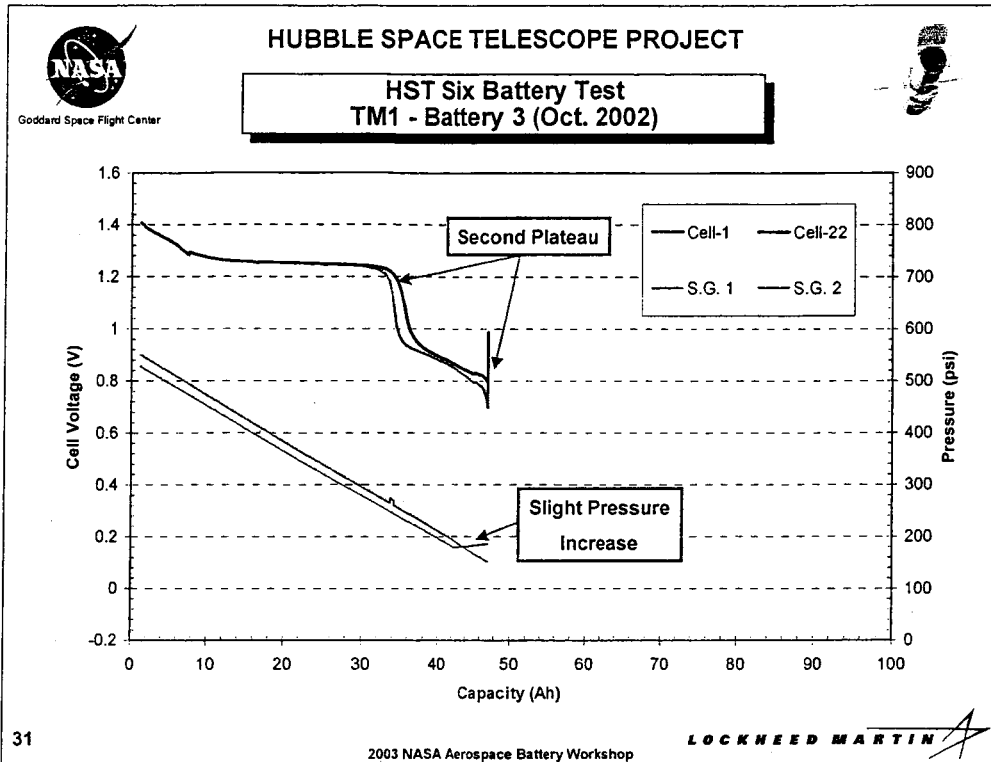
Similarly, the TM1 Battery 2 capacity check performed in 2002, indicates significant capacity fade, 2nd plateau, and cell drop outs.



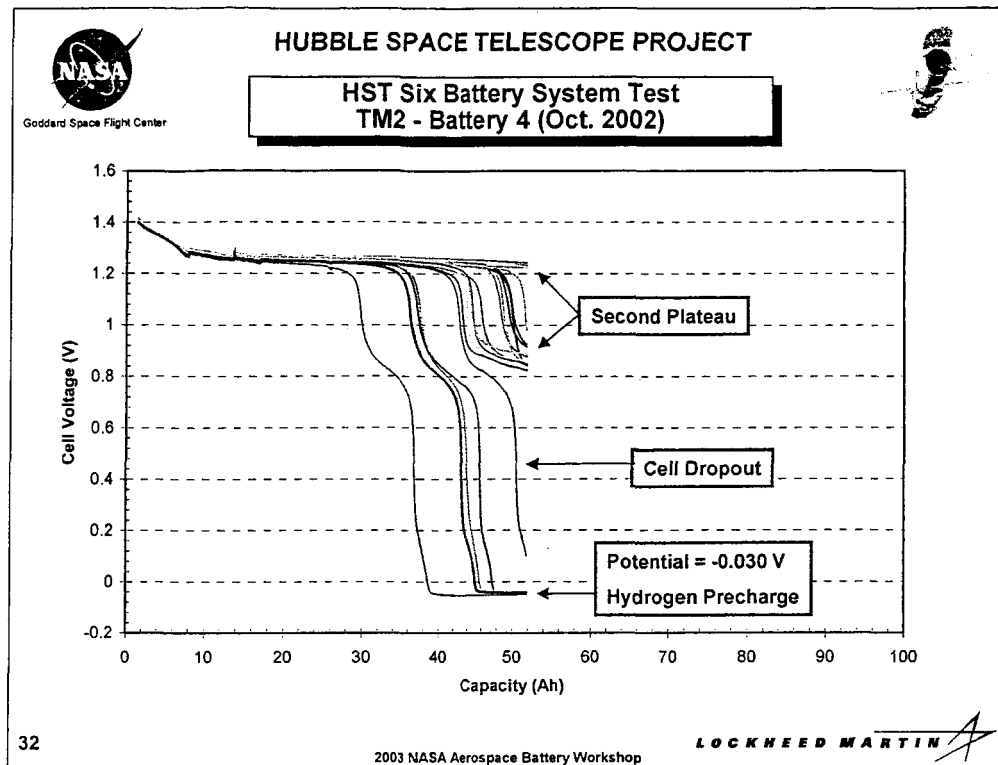
This chart, detailing the voltage and strain gauge pressures from the capacity check for TM1 Battery 2, performed in 2002, exhibits cell drop out, without the strain gauge pegging.



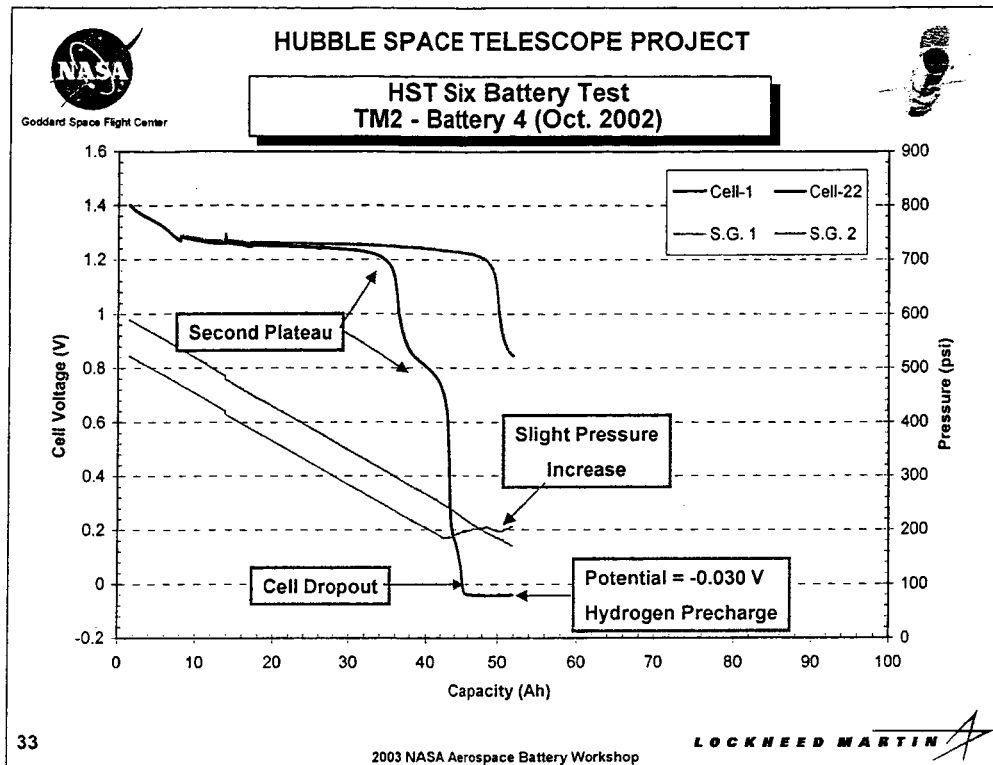
Similarly, the TM1 Battery 3 capacity check performed in 2002, indicates significant capacity fade, 2nd plateau, and cell drop outs.



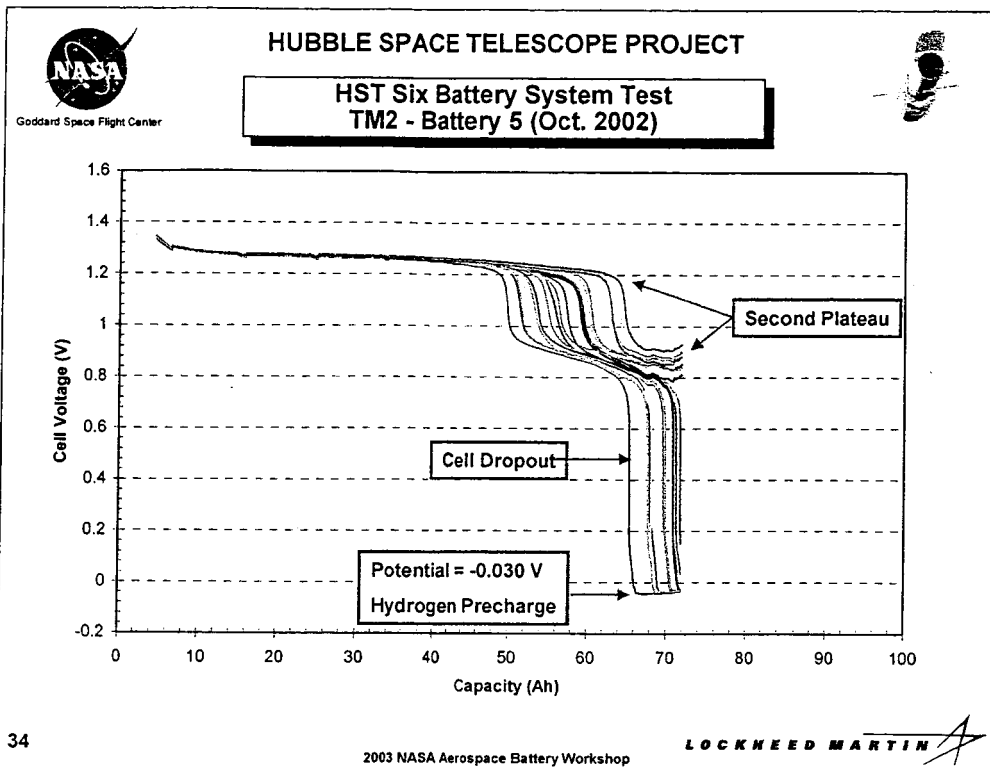
This chart, detailing the voltage and strain gauge pressures from the capacity check for TM1 Battery 3, performed in 2002, exhibits significant 2nd plateaus. Note that cell voltage for cell #22 does not reverse at the same time as its strain gauge pressure pgs. This suggests that cell #22 is close to being hydrogen limited.



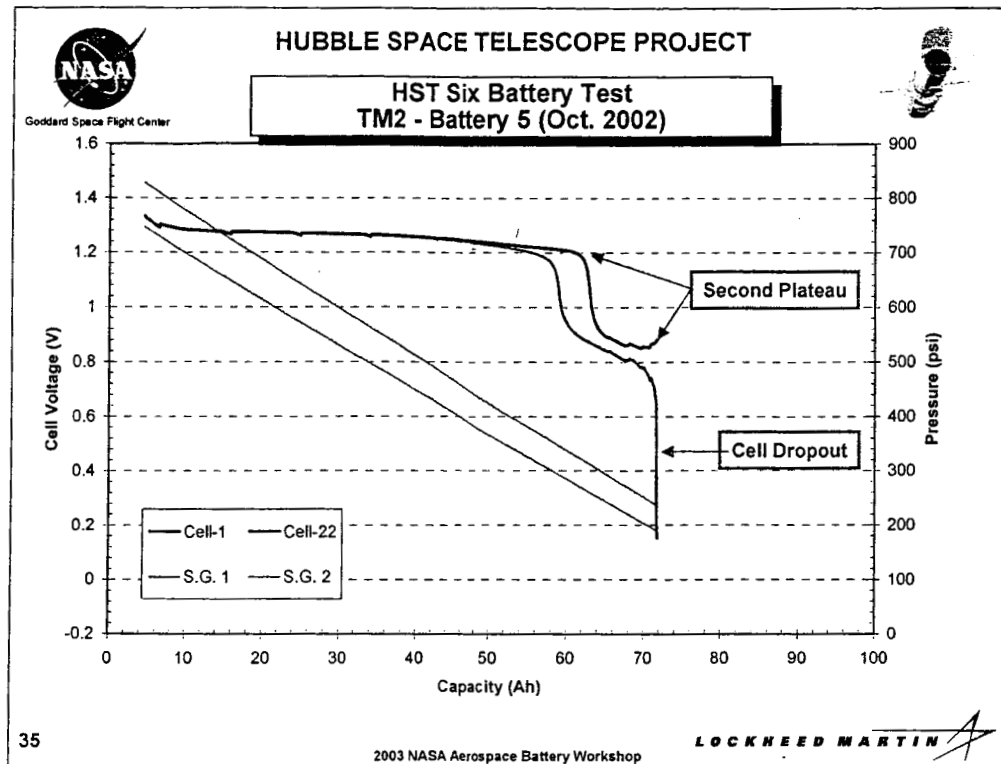
Similarly, the TM2 Battery 4 capacity check performed in 2002, indicates significant capacity fade, 2nd plateaus, and cell drop outs.



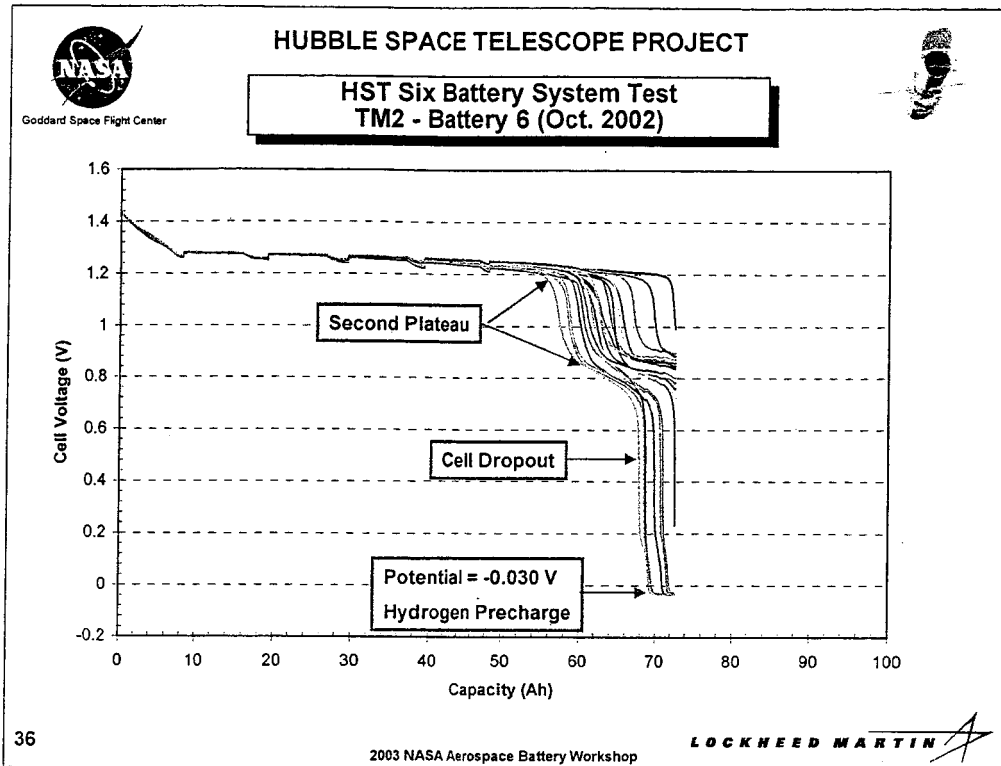
This chart, detailing the voltage and strain gauge pressures from the capacity check for TM2 Battery 4 performed in 2002 exhibit significant 2nd plateau, capacity dispersion, and cell drop out. Note that there is also wide disparity between the two strain gauge pressures, and their respective cell voltages.



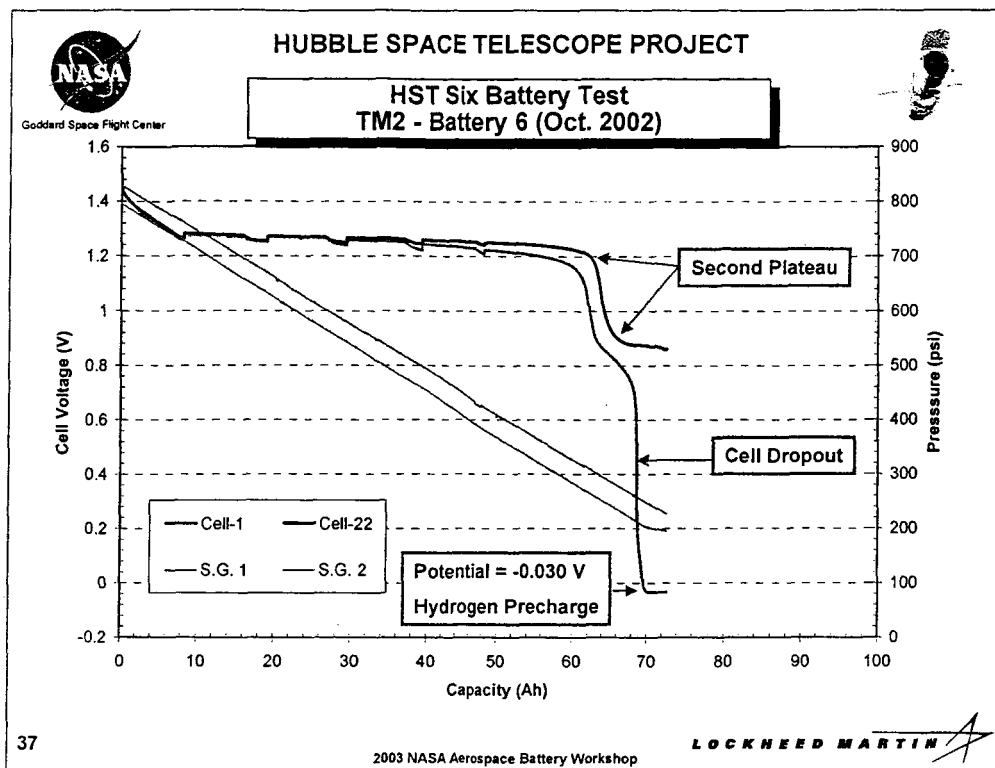
Similarly, the TM2 Battery 5 capacity check performed in 2002, indicates significant capacity fade, 2nd plateaus, and cell drop outs. However, it is important to note that the capacity of this battery is significantly higher than Batteries 1 - 4 which is due to this battery being maintained at a higher SOC during the Power Control Unit (PCU) bus-bar anomaly from 1998 to 2002.



This chart, detailing the voltage and strain gauge pressures from the capacity check for TM2 Battery 5 performed in 2002 exhibits significant 2nd plateaus, capacity dispersion, and cell drop out; note the higher pressure levels observed with these cells as a result of the higher SOC.



Similarly, the TM2 Battery 6 capacity check performed in 2002, indicates significant capacity fade, 2nd plateaus, and cell drop outs. However, note that the capacity of this battery is also significantly higher than Batteries 1 - 4 which is due to this battery being maintained at a higher SOC during the PCU bus-bar anomaly.



This chart, detailing the voltage and strain gauge pressures from the capacity check for TM2 Battery 6 performed in 2002 indicates significant voltage plateau degradation, capacity fade dispersion, 2nd plateau, and cell drop out. Note that cell voltage for cell #1 reverses at the same time as its strain gauge pressure pegs, indicating cell drop out is associated with pressure depletion.



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HST Flight Batteries Ageing Signatures



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HST Flight Batteries Ageing Signatures



-Voltage Curves From Orbital Capacity Checks Exhibit

- Voltage Plateau Degradation on All Batteries

- Capacity Fade on All Batteries

- Impedance Growth on All Batteries

- Cell Drop Out on All Batteries

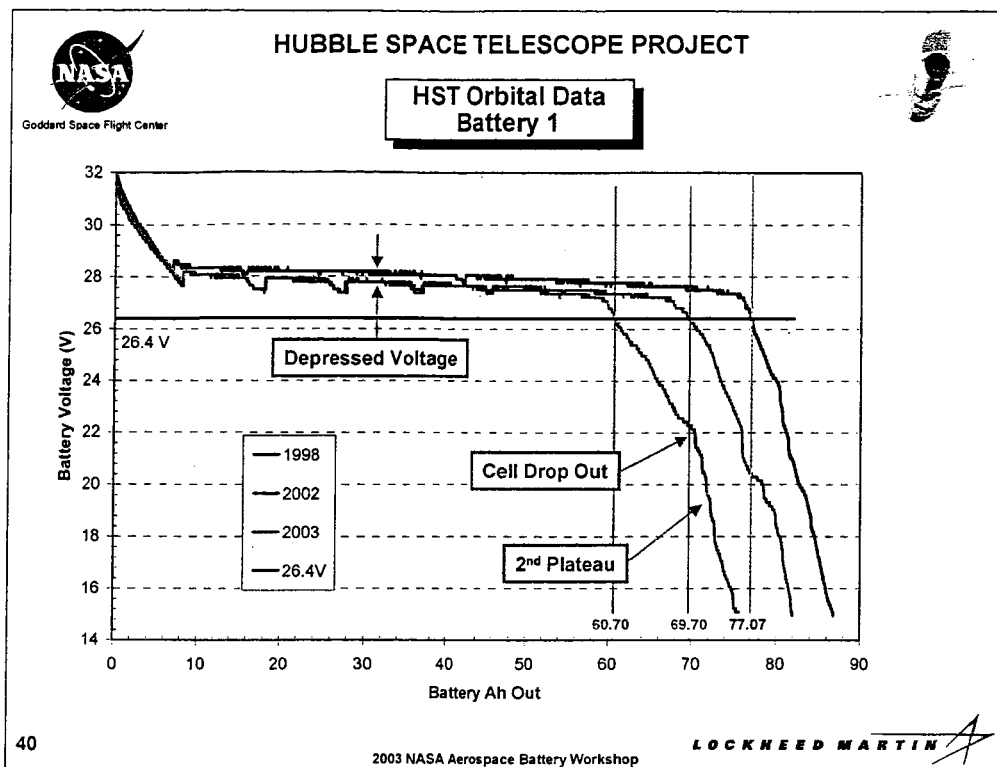
 - Signature is sudden >0.8 V Drop in Battery Voltage

- Second Plateau Formation on All Batteries

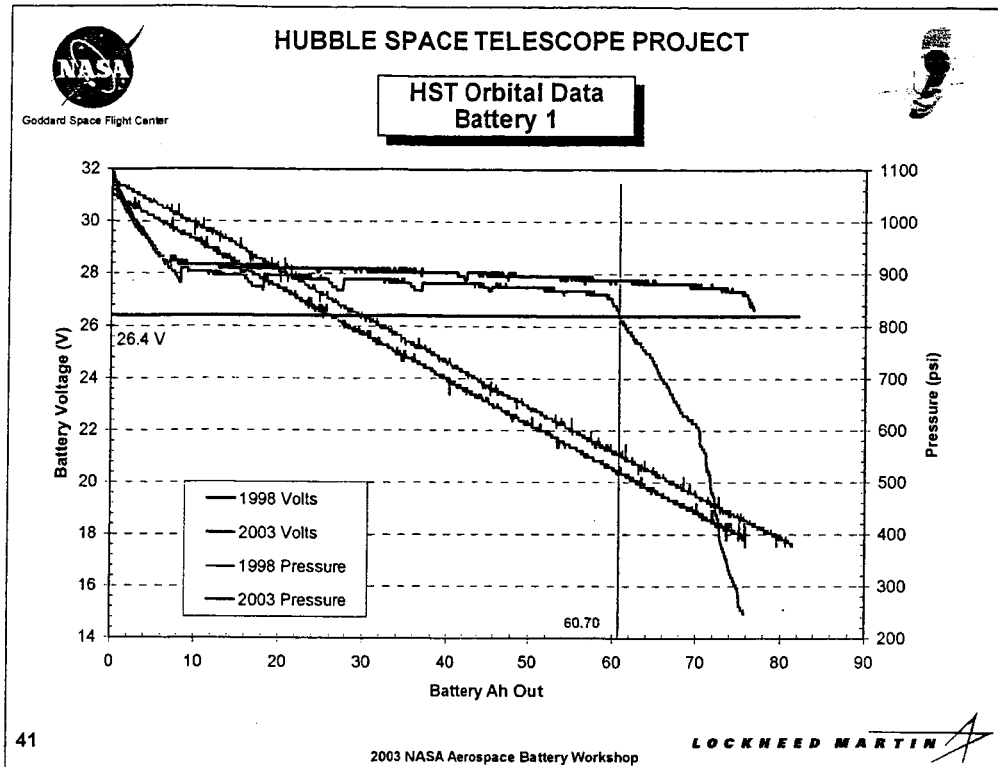
 - Second Plateau Signature <0.5 V

Capacity Check using 5.1 ohm Resistor across the Battery to 15 V

The on-orbit HST batteries, while having no individual cell monitor sensors, do exhibit similar voltage discharge signatures during capacity checks. Observed from these discharge curves are capacity fade, voltage plateau depression, impedance growth, 2nd plateau, and cell drop out.



Battery 1 has a depressed voltage plateau (voltage degradation), capacity fade, at least one cell drop out, and several cells displaying second plateau formation.



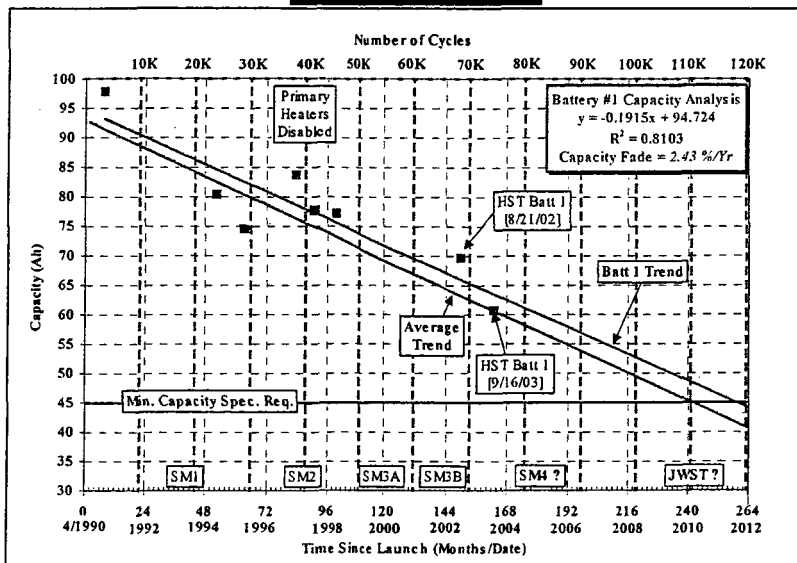
Battery 1 shows voltage plateau depression and significant capacity fade between 1998 and 2003. Correspondingly only a minor pressure drop is observed in the strain gauge data. The strain gauge pressure is calibrated after each capacity check and could impact these results.



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HST Orbital Data Battery 1



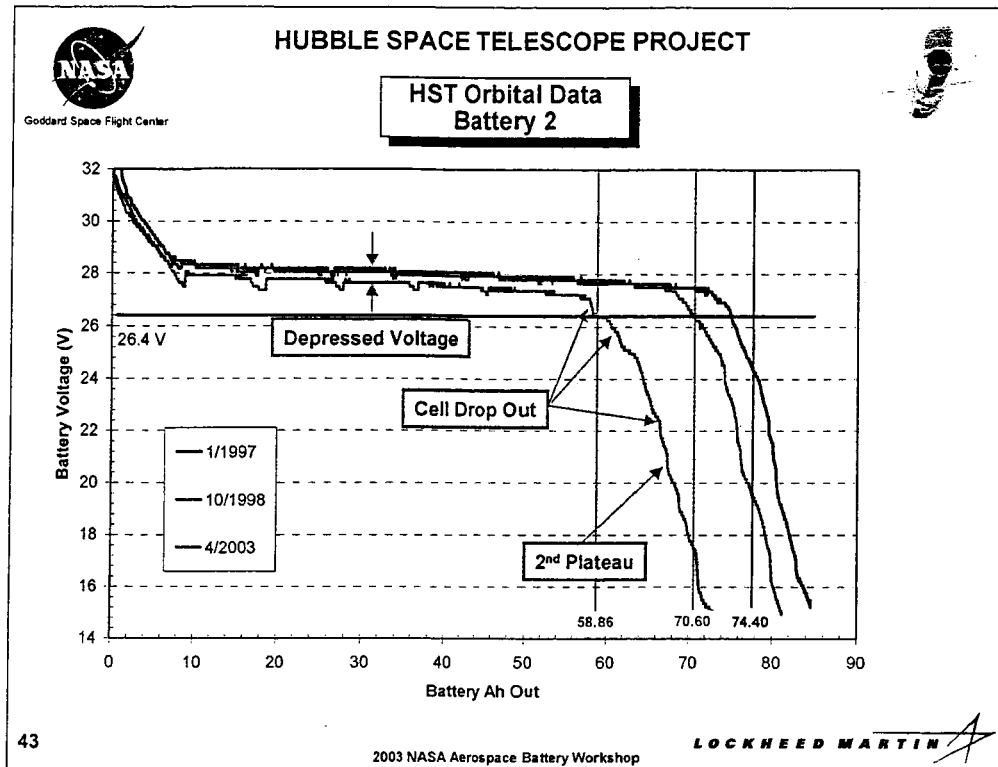
R^2 = Fit Coefficient (1.0 = Best)

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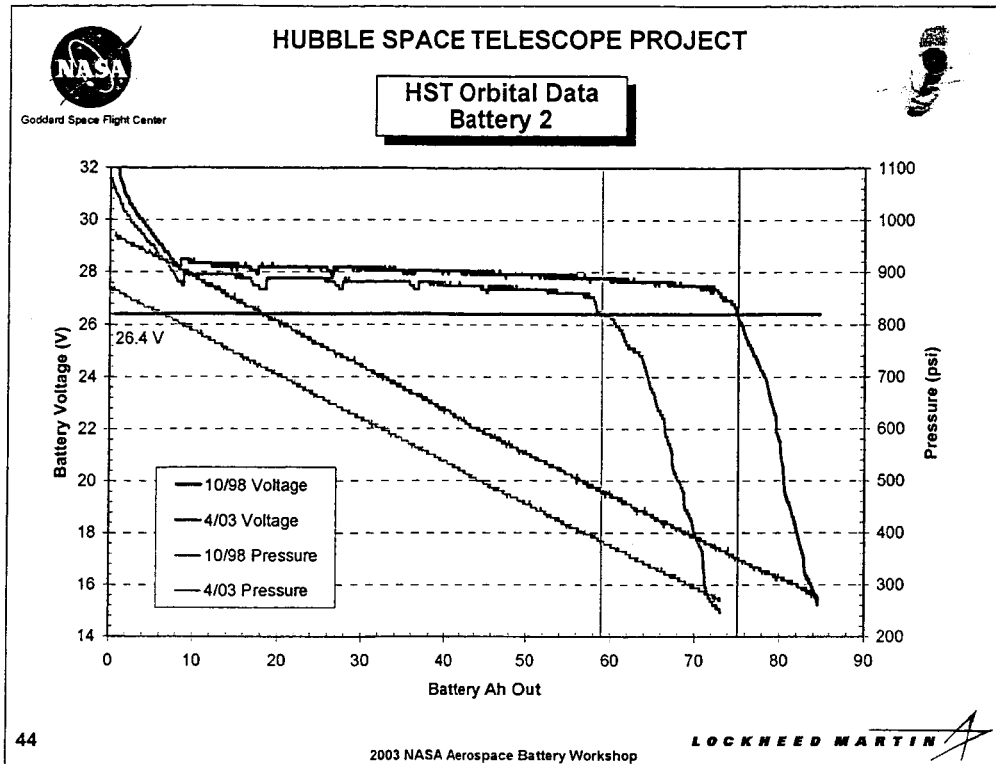
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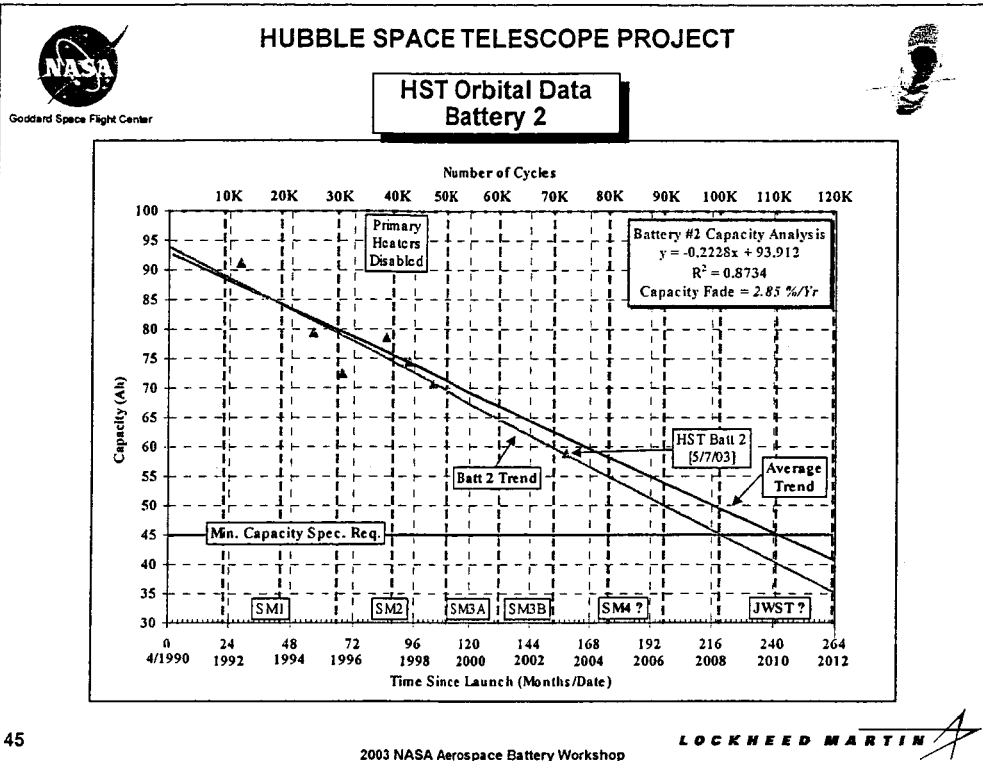
The Battery capacity fade trend suggests a battery 1 replacement in 2012 if the general trend (with a R^2 fit coefficient of 0.81) is used or 2005 if the trend from the last two reconditioning cycles were to continue.



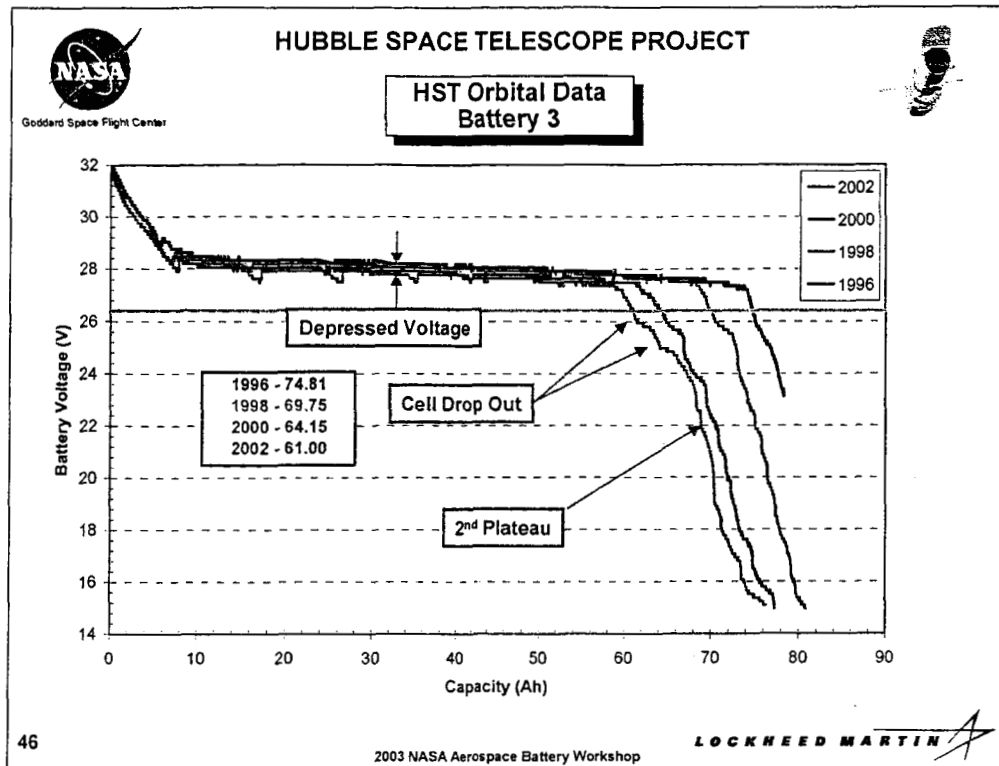
Battery 2 has a depressed voltage plateau (voltage degradation), capacity fade, at least two cells dropping out, and several cells displaying second plateau formation.



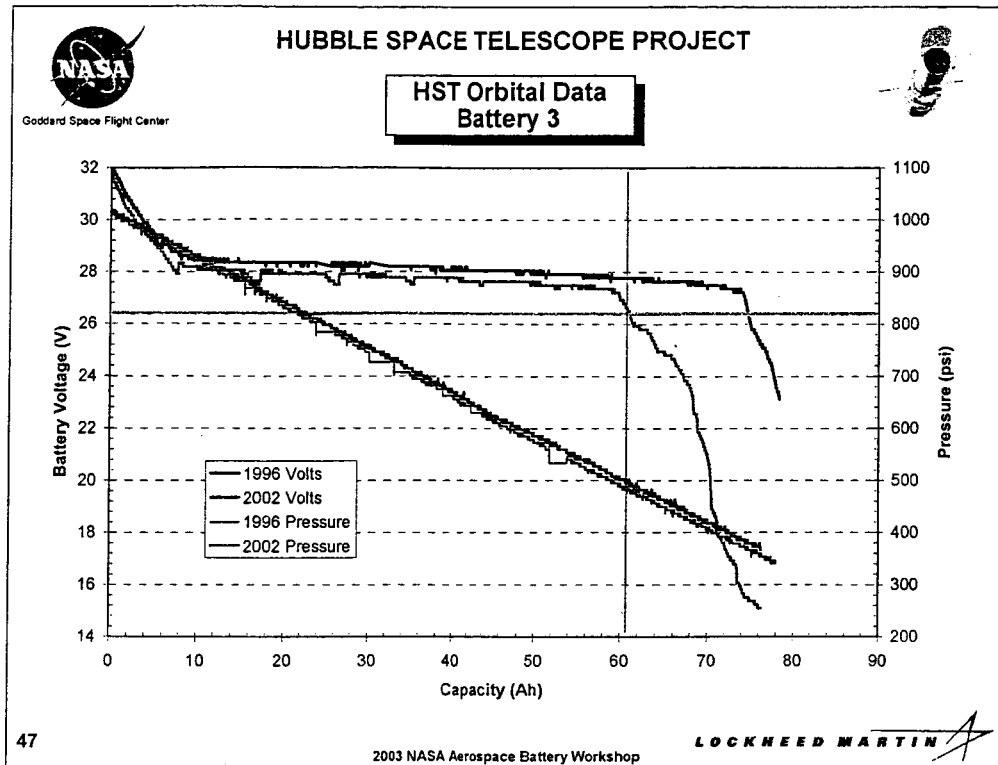
Battery 2 exhibits a depressed voltage plateau (voltage degradation) and capacity fade. The drop in strain gauge pressure between 1998 and 2003 indicates the batteries are not getting charged due to insufficient VT control Level and/or impedance growth.



The Battery capacity fade trend suggests a battery 2 replacement in 2008 if the general trend (with a R^2 fit of 0.87) is used.



Battery 3 has a depressed voltage plateau (voltage degradation), capacity fade, at least two cells dropping out, and several cells displaying second plateau formation.



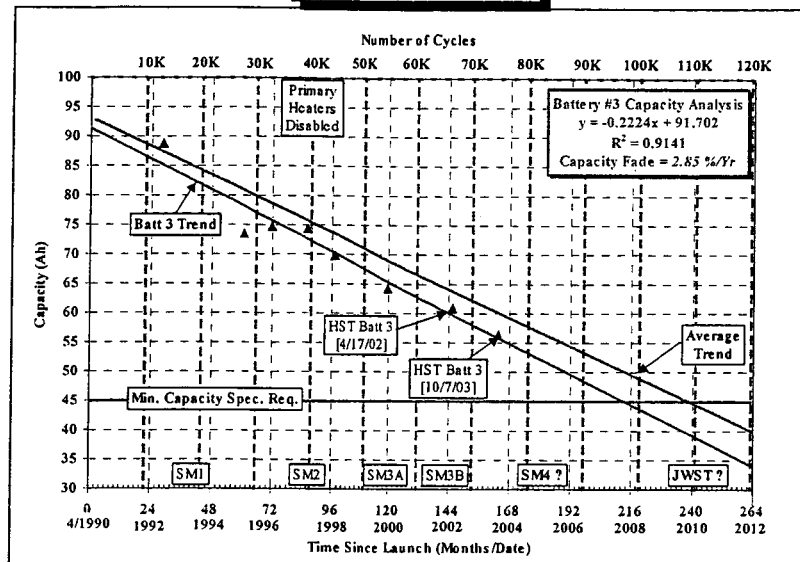
Battery 3 shows voltage plateau depression and significant capacity fade between 1996 and 2002, with only a minor pressure drop observed in the strain gauge data.



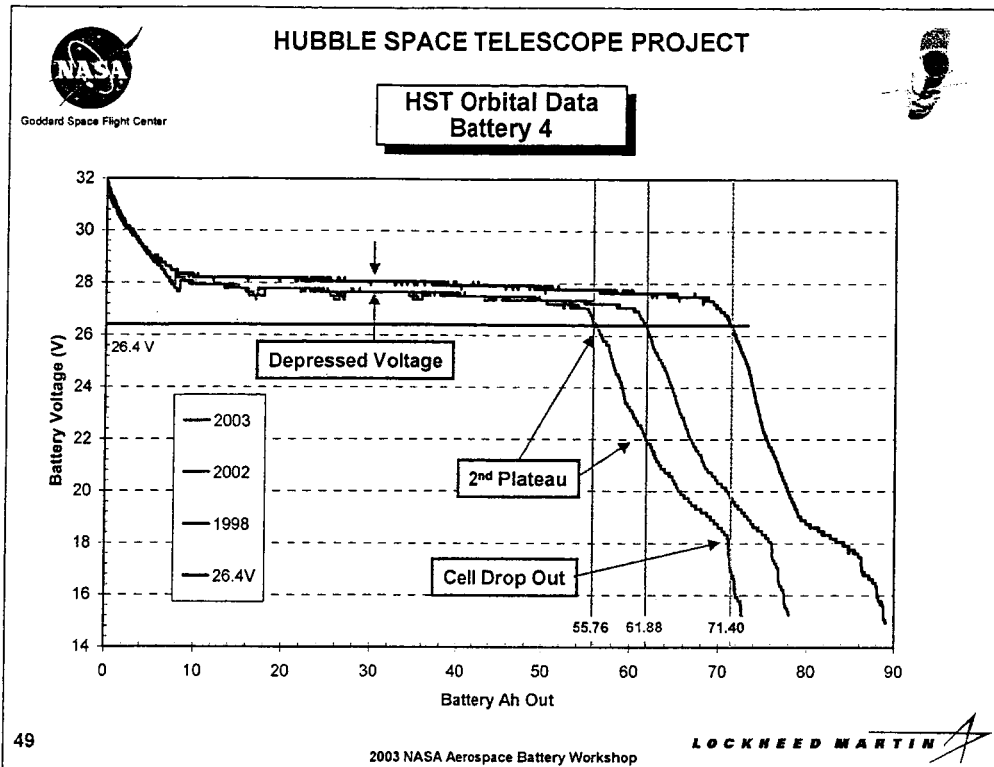
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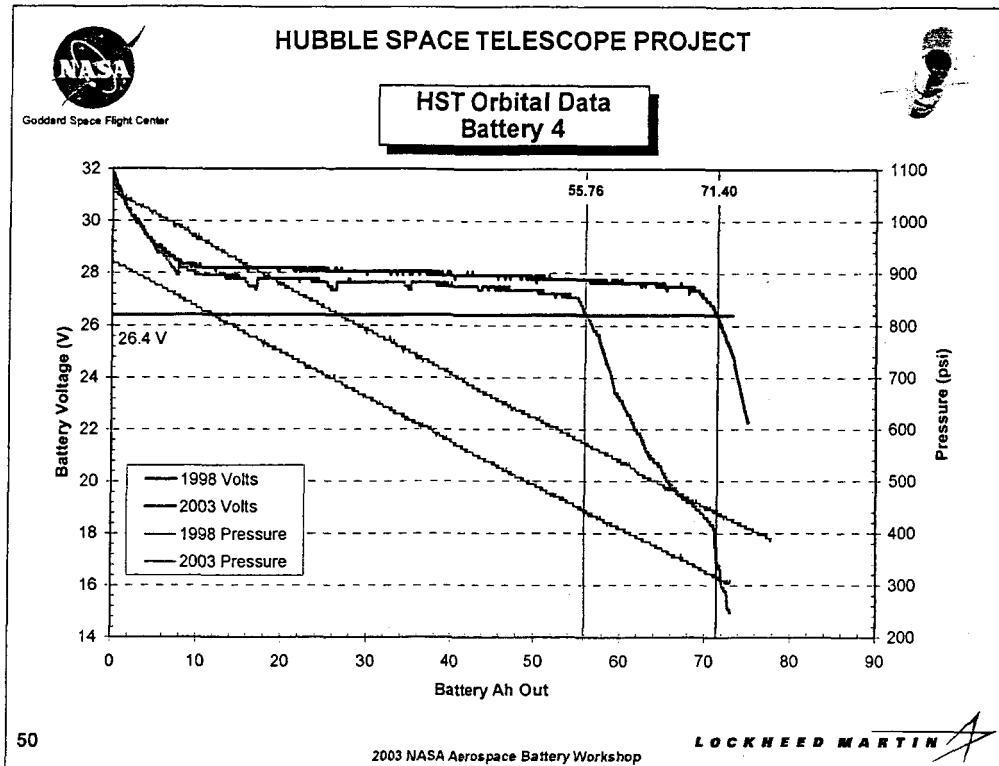
HST Orbital Data Battery 3



The Battery capacity fade trend suggests a battery 3 replacement in 2007 if the general trend (with a R^2 fit of 0.91 - fairly good fit) is used.



Battery 4 has a depressed voltage plateau (voltage degradation), capacity fade, at least one cell dropping out, and several cells displaying second plateau formation.



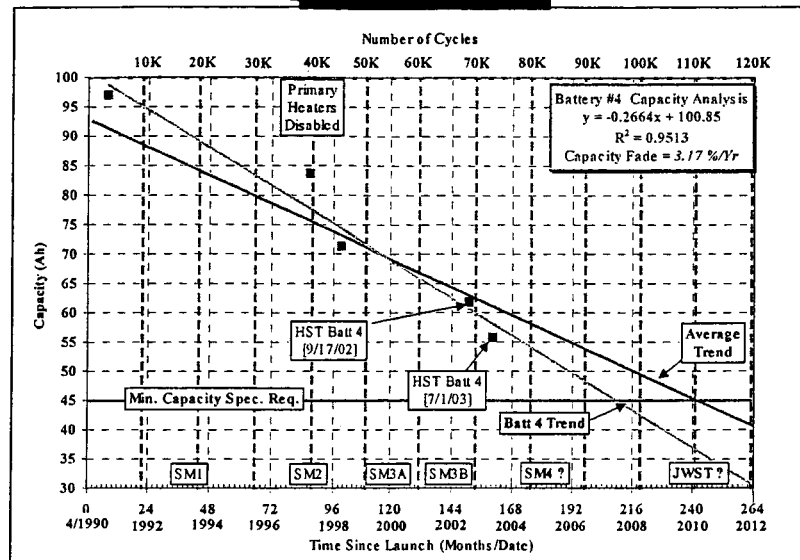
Battery 4 demonstrates a depressed voltage plateau (voltage degradation), capacity fade, at least one cell dropping out, and several cells displaying second plateau formation in the time between capacity checks performed in 1998 and 2003. The pressure fade of 135 psi (which equates roughly to 13.5 Ah) and the capacity fade of 15.6 Ah between capacity checks suggest insufficient VT charge level.



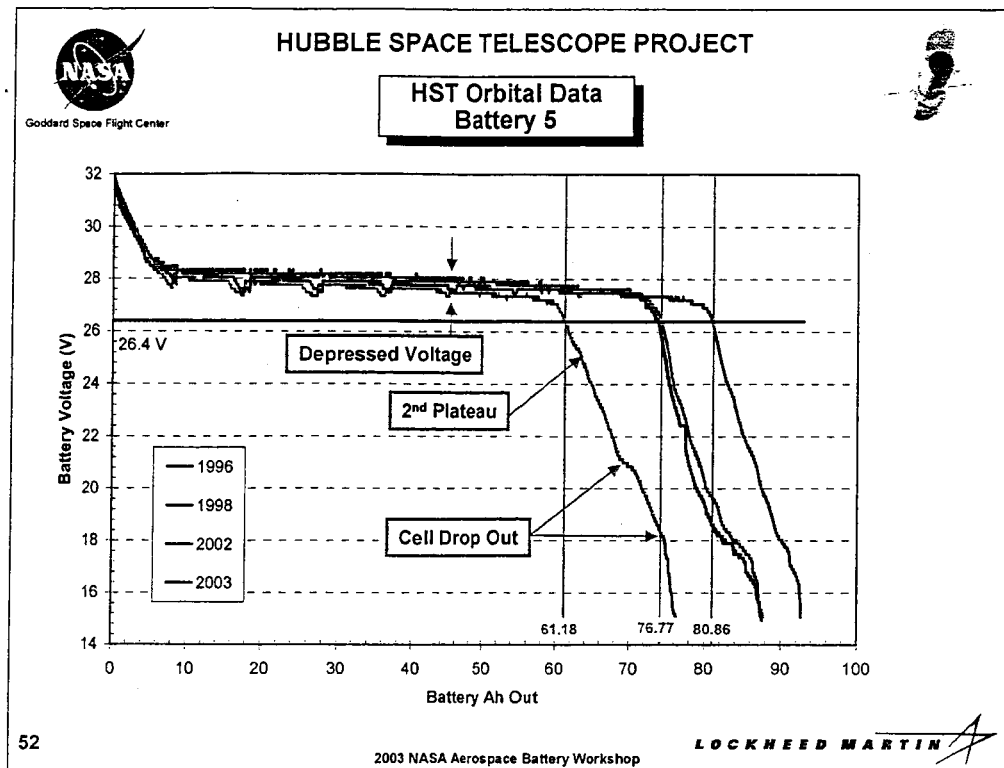
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HST Orbital Data Battery 4

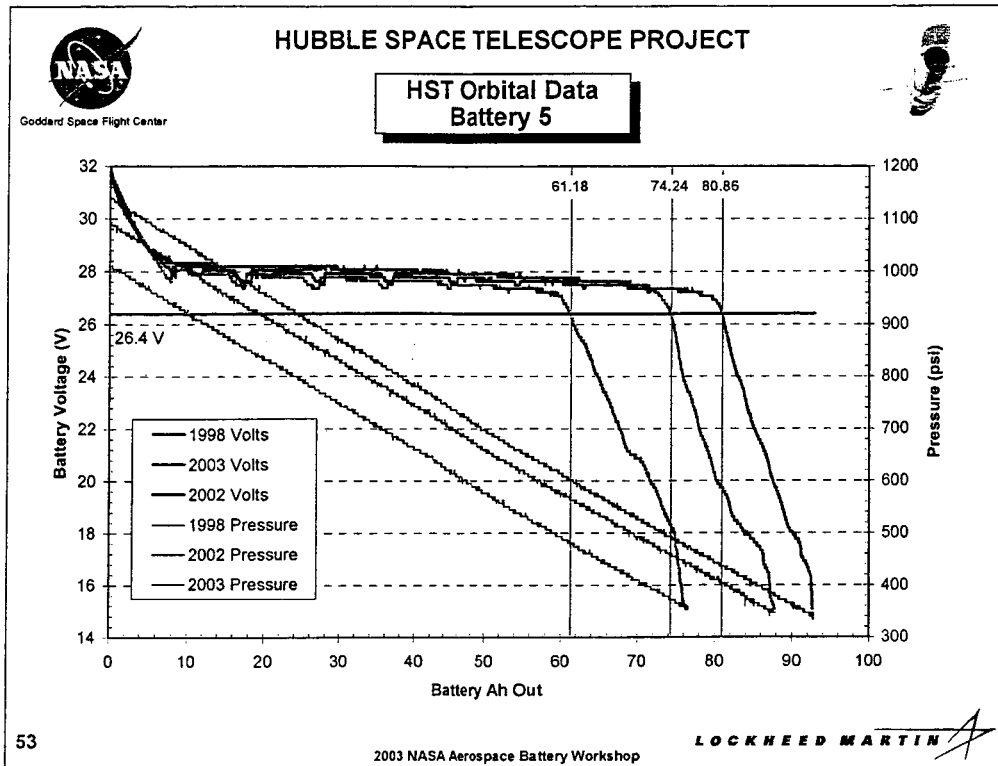


The Battery capacity fade trend suggests a battery 4 replacement in 2007 if the general trend (with a R^2 fit of 0.95 - very good fit) is used or 2005 if the trend from the last two reconditioning cycles were to continue.



Battery 5 has a depressed voltage plateau (voltage degradation), capacity fade, at least one cell dropping out, and several cells displaying second plateau formation.

Also evidenced on this chart is the voltage profile for the capacity test performed immediately after replacement of the PCU in 2002. Battery 5 having a long period of high SOC due to charger issues, returns a higher capacity of 74 Ah. This is then followed a year later with the lower capacity of 61 Ah.



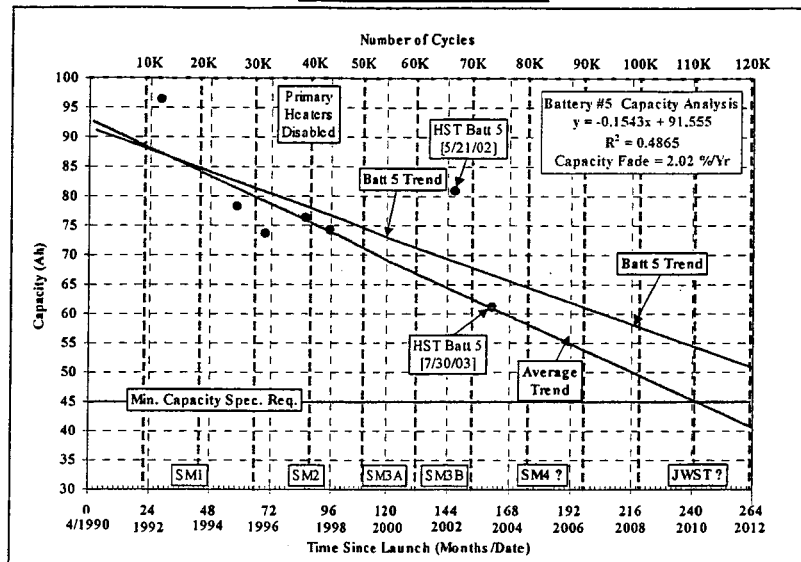
Battery 5 shows evidence of a depressed voltage plateau (voltage degradation), capacity fade, at least several cells dropping out, and several cells displaying second plateau formation in the time between capacity checks in 1998 and 2003. The strain gauge pressure for these two periods shows a pressure fade of about 90 psi (equates to about 9 Ah) and a capacity fade of 13 AH.



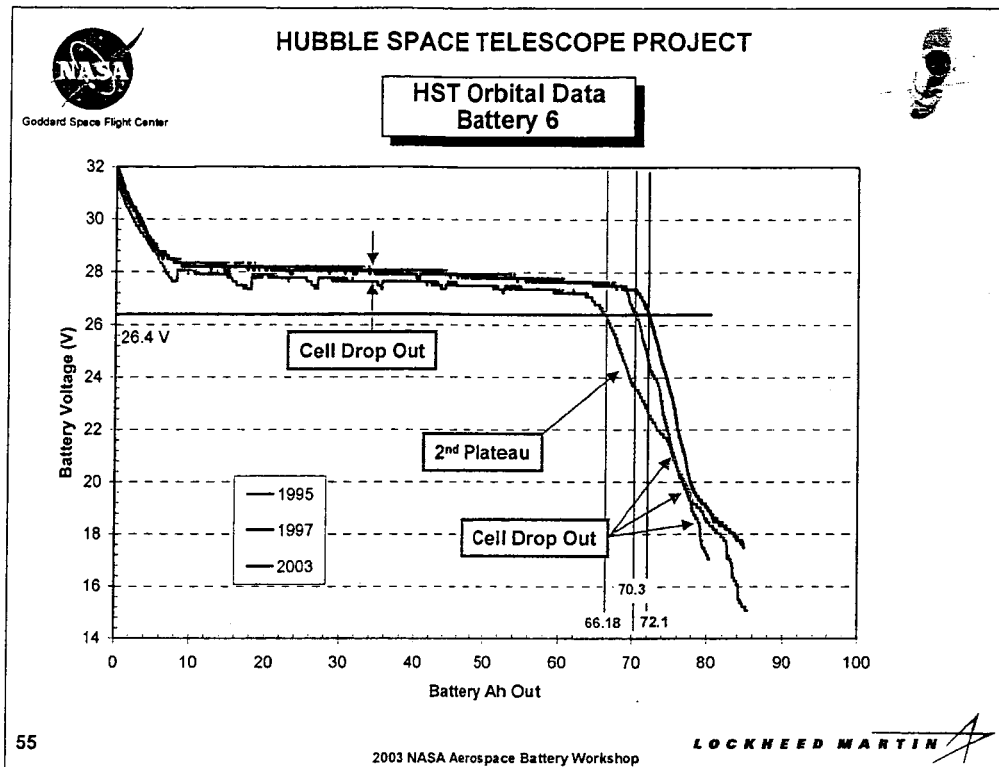
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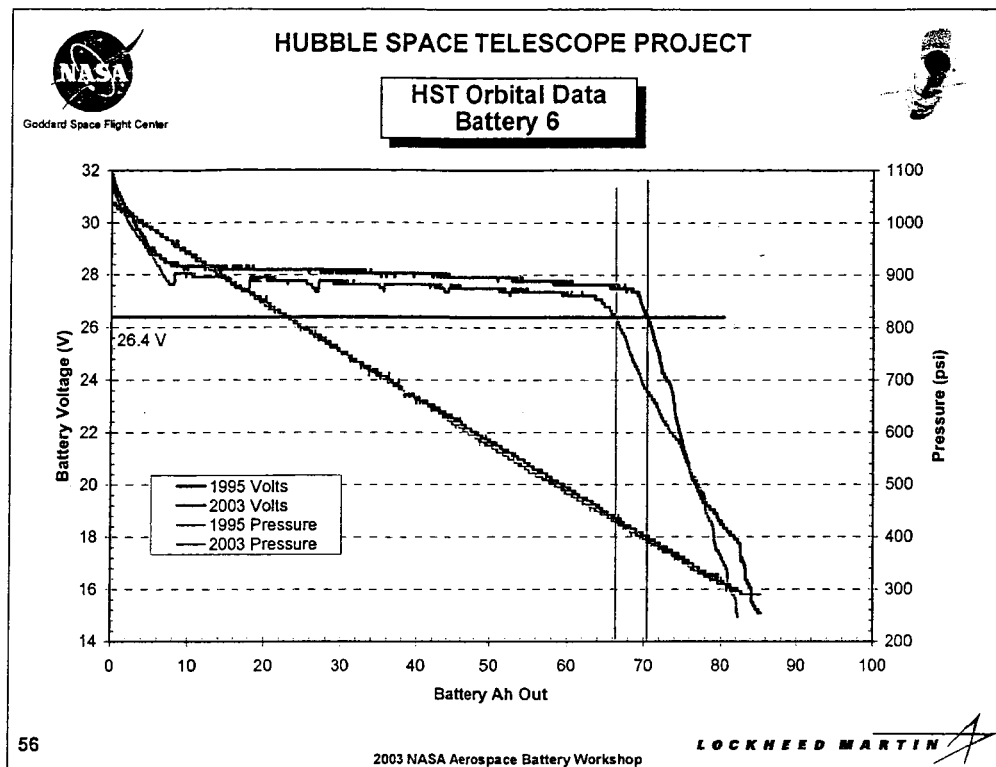
HST Orbital Data Battery 5



The Battery capacity fade trend suggests a Battery 5 replacement in 2014; however the R^2 fit is a poor 0.48, raising doubt with this projection. The fit is probably slewed high due to the long period that Battery 5 was held at a higher SOC (with the PCU bus fault which was repaired prior to the May 2002 Capacity Check).



Battery 6 has a depressed voltage plateau (voltage degradation), capacity fade, at least three cells dropping out, and several cells displaying second plateau formation.



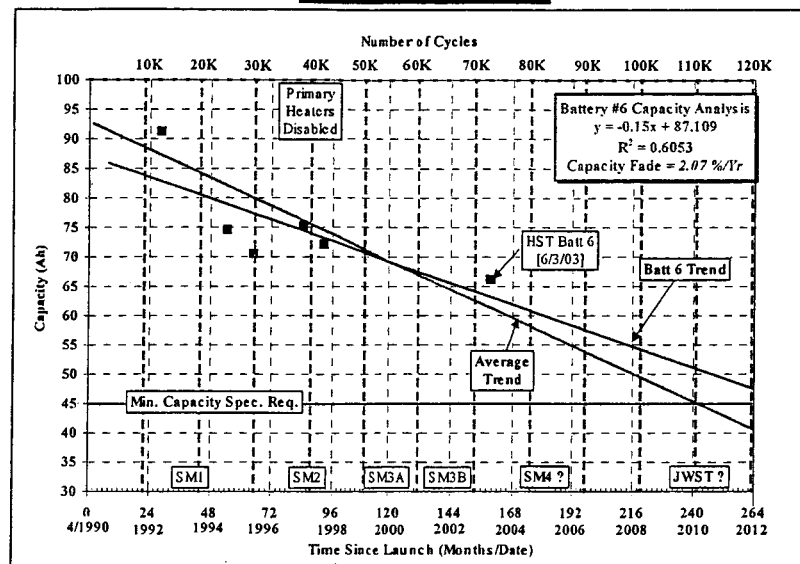
The pressure during the capacity checks performed in 1995 and 2003 are identical indicating this battery has been maintained at a good state of charge, and only minor capacity fade is observed in this time interval. This battery was also maintained at high SOC during the PCU charger anomaly.



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The Battery capacity fade trend suggests a battery 6 replacement in 2013. This is probably slewed high due to the long period that Battery 6 was held at a higher SOC (with the PCU bus fault which was repaired prior to the May 2002 Capacity Check).



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HST Orbital Data
Cycle Life Projections

-Cycle Life Projection Based Upon Minimum Capacity Requirement of 45 Ah/Battery

Since Launch (4/30/1990)

| | System | Bat 1 | Bat 2 | Bat 3 | Bat 4 | Bat 5 | Bat 6 |
|-------------------------|----------|----------|----------|----------|----------|----------|----------|
| Projected Life (Yrs) | 19.9 | 21.6 | 18.3 | 17.8 | 17.5 | 25.1 | 23.4 |
| Date (System Min Ah) | Mar-2010 | Dec-2011 | Aug-2008 | Feb-2008 | Oct-2007 | Jun-2015 | Sep-2013 |
| R ² | 0.71 | 0.81 | 0.87 | 0.94 | 0.95 | 0.49 | 0.61 |
| Capacity Fade (% Ah/Yr) | 2.60 | 2.43 | 2.85 | 2.85 | 3.17 | 2.02 | 2.07 |

Since Primary Heaters Disabled (1997 -)

| | System | Bat 1 | Bat 2 | Bat 3 | Bat 4 | Bat 5 | Bat 6 |
|-------------------------|----------|----------|----------|----------|----------|----------|----------|
| Projected Life (Yrs) | 20.6 | 20.1 | 17.6 | 18.0 | 16.5 | 33.4 | 29.3 |
| Date (System Min Ah) | May-2010 | May-2010 | Dec-2007 | Apr-2008 | Oct-2006 | Sep-2023 | Jul-2019 |
| R ² | 0.58 | 0.91 | 0.98 | 0.97 | 0.91 | 0.20 | 0.94 |
| Capacity Fade (% Ah/Yr) | 2.62 | 2.76 | 3.08 | 2.84 | 3.53 | 1.42 | 1.57 |

Since SM3B (4/2002 -)

| | System | Bat 1 | Bat 2 | Bat 3 | Bat 4 | Bat 5 | Bat 6 |
|-------------------------|----------|----------|-------|----------|----------|----------|-------|
| Projected Life (Yrs) | 15.4 | 15.5 | n/a | 17.4 | 14.8 | 14.4 | n/a |
| Date (System Min Ah) | Jul-2005 | Oct-2005 | n/a | Sep-2007 | Feb-2005 | Sep-2004 | n/a |
| R ² | 0.32 | 1.00 | n/a | 1.00 | 1.00 | 1.00 | n/a |
| Capacity Fade (% Ah/Yr) | 4.79 | 4.78 | n/a | 3.09 | 4.84 | 5.82 | n/a |

Last Recondition

| | System | Bat 1 | Bat 2 | Bat 3 | Bat 4 | Bat 5 | Bat 6 |
|---------------|--------|---------|--------|---------|--------|---------|--------|
| Capacity (Ah) | n/a | 60.70 | 58.86 | 56.40 | 55.78 | 61.18 | 66.15 |
| Date | n/a | 9/16/03 | 5/7/03 | 10/7/03 | 7/1/03 | 7/30/03 | 6/2/03 |

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Table summarizes the system and individual battery capacity fade rates and projects a date for replacement.

The top table summarizes the data since launch.

The second data set provides a projection since the primary heaters were disabled.

The third set examines the trend since the Power Conditioning Unit was replaced in 2002 during SM3B. Since that time, 4 of the 6 batteries have undergone 2 capacity checks with trends reported herein. Near-term battery replacement is required if these trends were to continue.

The last data set lists the date and capacity of the last capacity check for each battery.



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HST Orbital Conclusions



- On Orbit Ageing Signatures Observed on All Flight Batteries Reveal
 - Cell Drop Out
 - Capacity Fade
 - Impedance Growth
 - Second Plateau
 - Depressed Discharge Voltage Plateau

- Battery Capacity Fade Trending Now Projects July 2005 Replacement or Sooner

The on-orbit capacity check cycles are examined and all flight batteries have the characteristic signatures of voltage degradation, capacity fade, second plateau formation, with batteries # 2, 3, and 4 having the highest capacity fade rates.



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